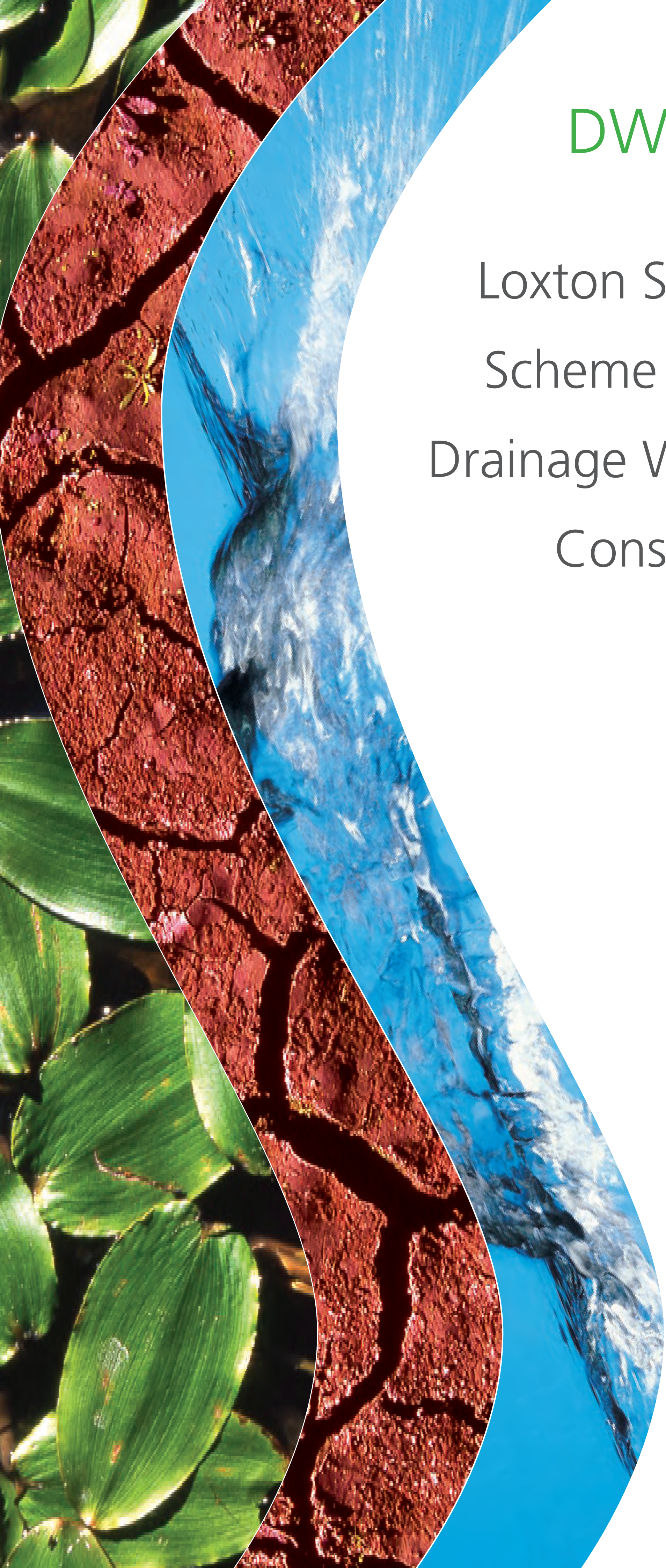

DWLBC REPORT

Loxton Salt Interception Scheme Trial Horizontal Drainage Well Design and Construction Report

2005/46

Government of South Australia
Department of Water, Land and Biodiversity Conservation

Loxton Salt Interception Scheme Trial Horizontal Drainage Well Design and Construction Report

Adrian Costar, Stephen Howles, Michael Stadter and Tony Hill

Knowledge and Information Division
Department of Water, Land and Biodiversity Conservation

July 2006

Report DWLBC 2005/46

Government of South Australia
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FOREWORD

South Australia's unique and precious natural resources are fundamental to the economic and social wellbeing of the State. It is critical that these resources are managed in a sustainable manner to safeguard them both for current users and for future generations.

The Department of Water, Land and Biodiversity Conservation (DWLBC) strives to ensure that our natural resources are managed so that they are available for all users, including the environment.

In order for us to best manage these natural resources it is imperative that we have a sound knowledge of their condition and how they are likely to respond to management changes. DWLBC scientific and technical staff continues to improve this knowledge through undertaking investigations, technical reviews and resource modelling.

Rob Freeman
CHIEF EXECUTIVE
DEPARTMENT OF WATER, LAND AND BIODIVERSITY CONSERVATION

ACKNOWLEDGEMENTS

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CONTENTS

CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Run-of-river salinity surveys indicate that a salt load of approximately 98 tonnes/day enters the River Murray in the Loxton reach (river kilometre 482–500) at flows of less than 5000 ML/day. The salt load may double to 188 tonnes/day at flows of 20 000–30 000 ML/day.

The Department of Water, Land and Biodiversity Conservation (DWLBC), in partnership with the Murray Darling Basin Commission (MDBC), and SA Water are constructing a Salt Interception Scheme (SIS) to address the problem. The MDBC and the State Government jointly fund the SIS through the National Action Plan for Salinity and Water Quality.

The Loxton SIS aims to intercept this highly saline groundwater through the construction and operation of a curtain of conventional vertical wells located on the floodplains. Pumping these wells will control the groundwater gradient that exists towards the River Murray by reducing the groundwater table to river pool level. However, approximately one third of the salt load entering the river in the Loxton reach comes from the highland areas where there is no floodplain adjacent the river. In the highland areas, conventional vertical wells may not provide cost effective or hydraulically efficient interception, and horizontal drainage wells were proposed as a potential solution. This novel approach has not been used in salt interception to date, and an actively pumping horizontal well of the design complexity that has been implemented, has perhaps not been used anywhere.

Construction of the trial horizontal drainage well commenced in July 2005 and was successfully completed by early August 2005. The horizontal drainage well targets a thin but persistent layer up to 2 m in thickness, comprising poorly sorted sands and reworked shell material.

While completion of the trial horizontal drainage well has been successful, and its hydraulic performance is outstanding, the decision to drill similar operational scale wells in the Loxton region will be determined following completion of a detailed analysis of the effectiveness of the well in controlling the groundwater flux and salt load entering the River Murray. At the time of writing long-term pumping tests are underway to assess the hydraulic performance of the well, in terms of well efficiency, development of drawdown, and infiltration of sand. These issues will be reported separately.

This report details the design and construction of the $1.2 m trial horizontal drainage well that has a total length of 500 m and an operational horizontal production zone length of 270 m. The technical problems that were encountered during the drilling, construction and development of the well are discussed. The successful completion of the well was partly due to the robust drilling contract, and recommendations applicable to future tenders and drilling contracts are discussed.

1. INTRODUCTION

1.1 BACKGROUND

The Loxton irrigation area is located adjacent to the River Murray in the northwest region of the Murray Basin (Fig. 1).

Prior to European settlement, a naturally occurring flux of saline groundwater entered the River Murray in the Loxton area, South Australia. This groundwater flux was very small in comparison to the current post-irrigation development flux, which is driven by the existence of a large groundwater mound that has developed in response irrigation drainage. A small groundwater flux associated with clearing of the Mallee area for dryland farming will also affect the river in the future.

Run-of-river salinity surveys indicate that a salt load of approximately 98 tonnes/day enters the River Murray in the Loxton reach (river kilometre 482–500) at flows of less than 5000 ML/day. The salt load may double to 188 tonnes/day at flows of 20 000–30 000 ML/day.

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DWLBC identified four sites in the Loxton region (Fig. 2) as being potentially suitable sites for horizontal drainage wells. Once completed, these horizontal drainage wells would link into the disposal pipeline servicing the conventional vertical wells currently being constructed at various locations on the River Murray floodplain. In mid-2004, it was proposed to construct a trial horizontal drainage well within one of these sites located approximately 10 km north of Loxton, completed at the base of the Loxton Sands.

The DWLBC Loxton numerical groundwater flow model is capable of predicting the fluxes of groundwater (and salt loads) entering the River Murray (Yan et. al. 2005a). The project site spans model Zone-26 and Zone-27 (Figs 3a and 3b) that are adjacent to the location of the trial horizontal drainage well, and jointly contribute 15.5 tonnes/day of salt to the river by lateral flow.

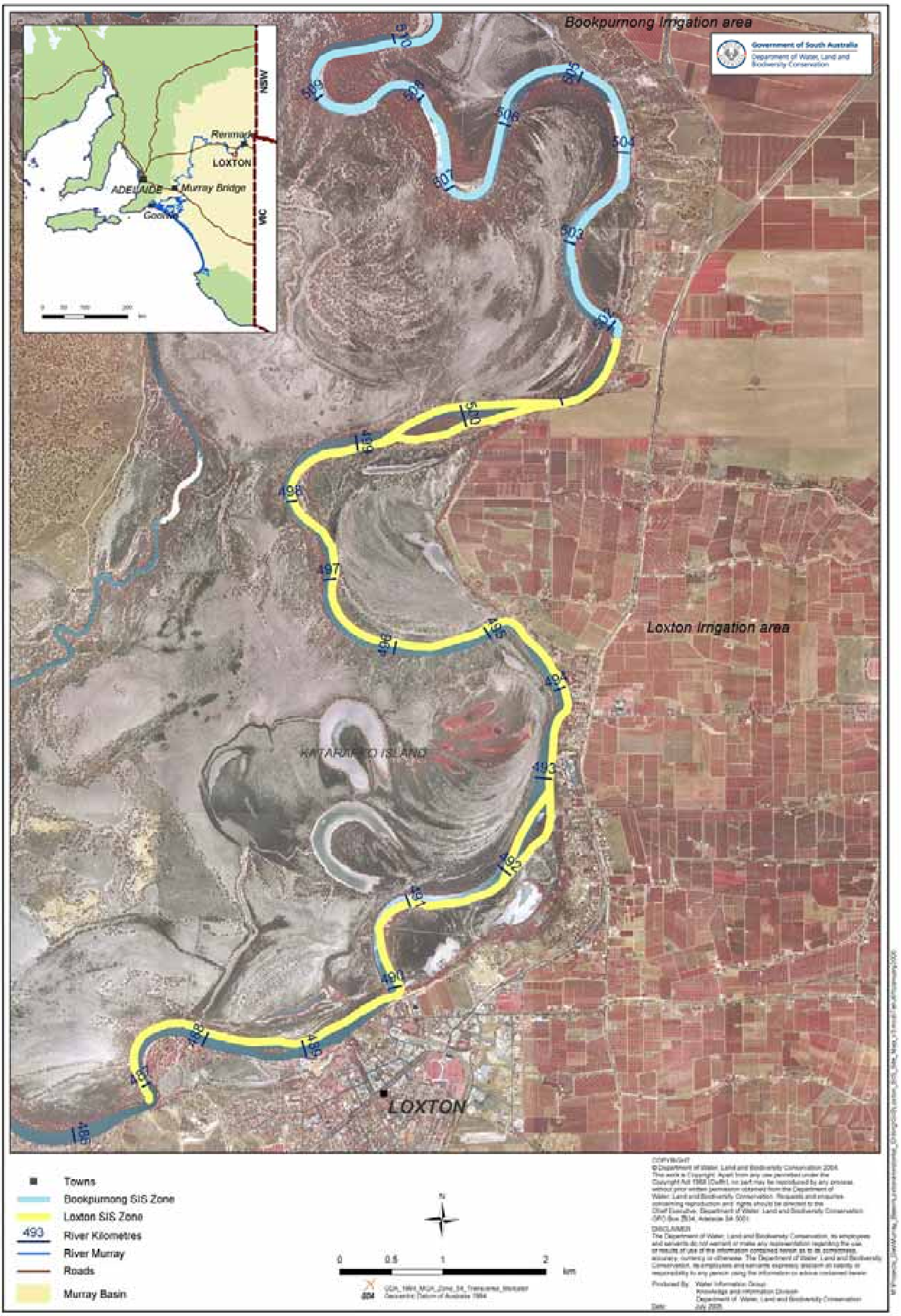

Figure 1. Location of project area

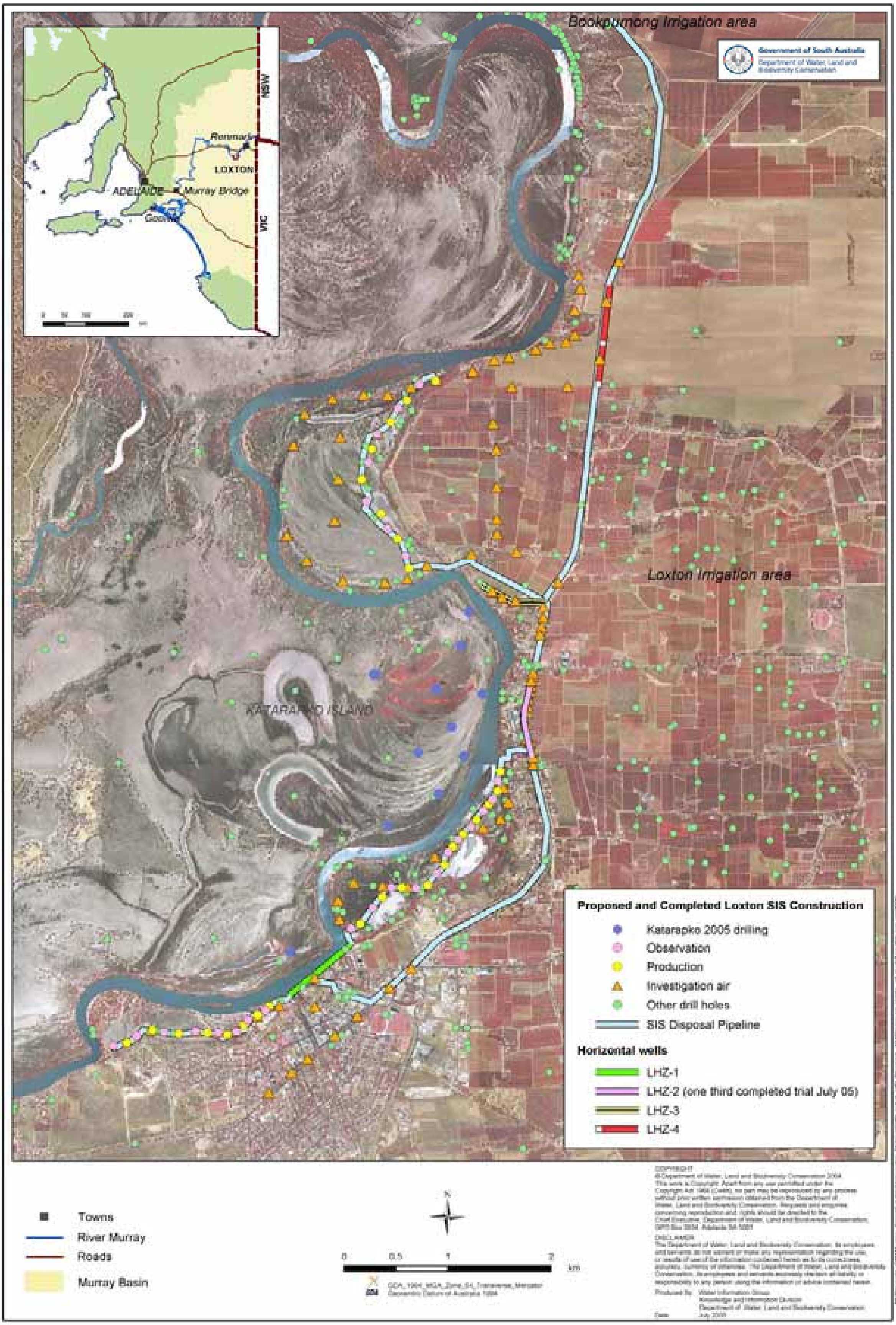

Figure 2. Loxton SIS location of conventional vertical wells and horizontal drainage wells (proposed and completed)

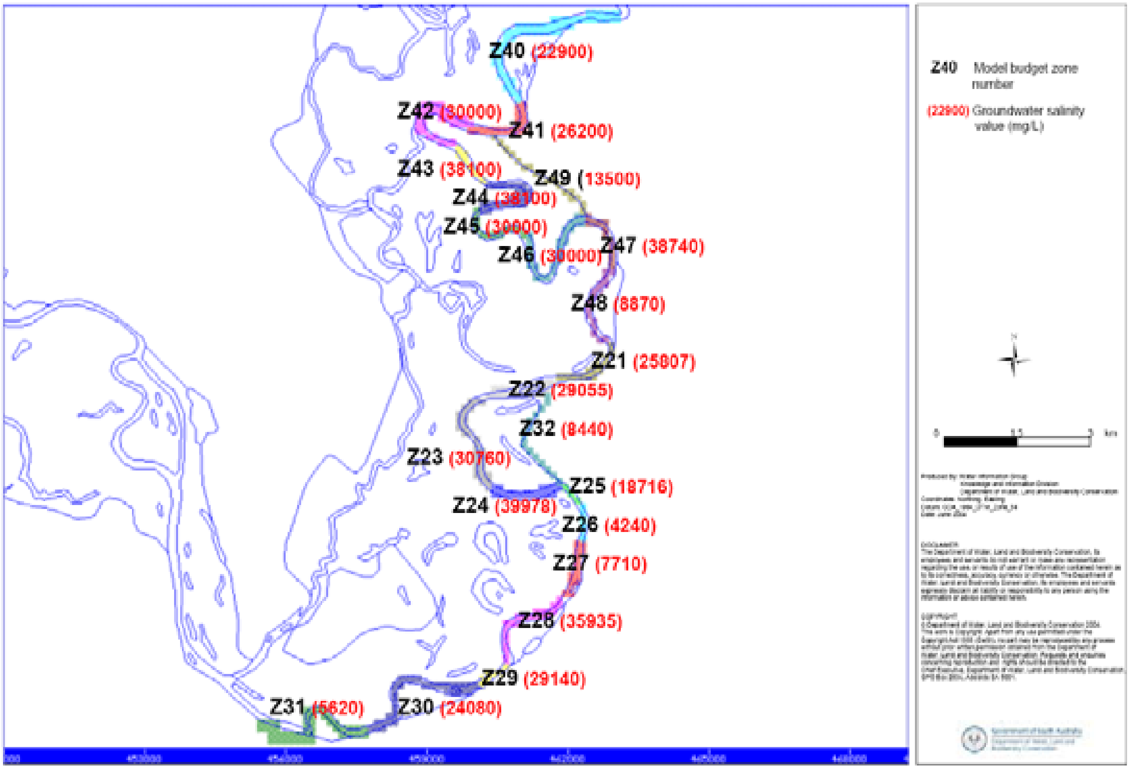

Figure 3a. Model flow budget zones in Layer-1 (Loxton Sands and Monoman Formation) and groundwater salinity values (TDS mg/L) in the Loxton – Bookpurnong area (Yan et. al. 2005b)

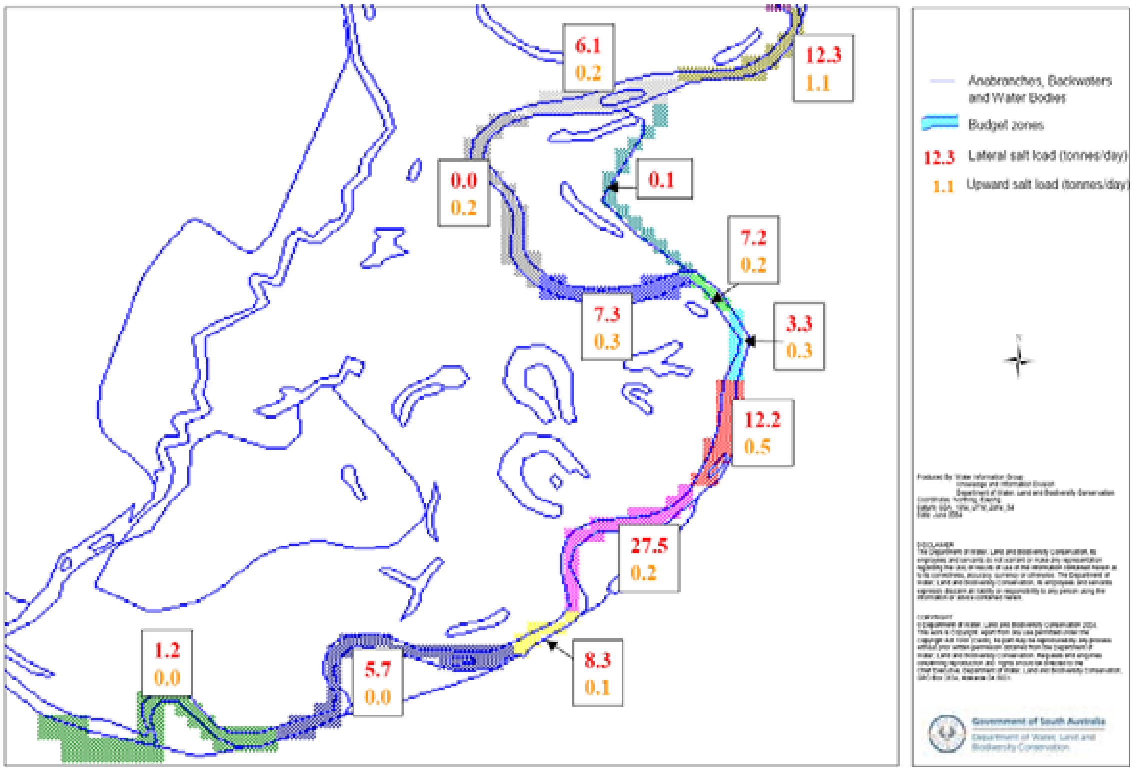

Figure 3b. Model flow budget zones Layer-1 and modeled 2002 salt load (tonnes/day) in the Loxton area (Yan et. al. 2005b)

While completion of the trial horizontal drainage well has been successful, and its hydraulic performance is outstanding, the decision to drill similar operational scale wells in the Loxton region will be determined following completion of a detailed analysis of the effectiveness of the well in controlling the groundwater flux and salt load entering the River Murray. At the time of writing long-term pumping tests are underway to assess the hydraulic performance of the well, in terms of well efficiency, development of drawdown, and infiltration of sand. These issues will be reported separately.

This project, involving the installation of a trial horizontal drainage well, has provided DWLBC with the technical and contractual knowledge and understanding of how such a project can be successfully completed.

Aside: Horizontal Directional Drilling:

The technology for Horizontal Directional Drilling (HDD) was developed for the petroleum industry, and has found wide application in the installation of services in Australia and overseas. Horizontal drilling has been documented as being used for the installation of drainage wells overseas, however in Australia it is a new concept, particularly for salt interception.

1.2 OBJECTIVES

The objectives of the project were to:

1. Demonstrate the feasibility of using horizontal drilling to install a trial horizontal drainage well in the Loxton Sands shell hash unit with a total operational horizontal component of approximately 250 m (note that additional wells would be required to provide full interception of salt at this site).
2. Demonstrate that the trial horizontal drainage well could be successfully developed.
3. Determine the hydraulic performance of the trial horizontal drainage well, in terms of drawing the groundwater table down to the level of the well, and operational issues associated with the well (reported separate from this report).
4. Refine contractual issues through the development and administration of a drilling contract for a horizontal drainage well.

2. REGIONAL HYDROGEOLOGY

The two principal aquifers targeted for salt interception in the Loxton region are the Loxton Sands in the highland area and Monoman Formation in the floodplain adjacent to the River Murray (Fig. 4).

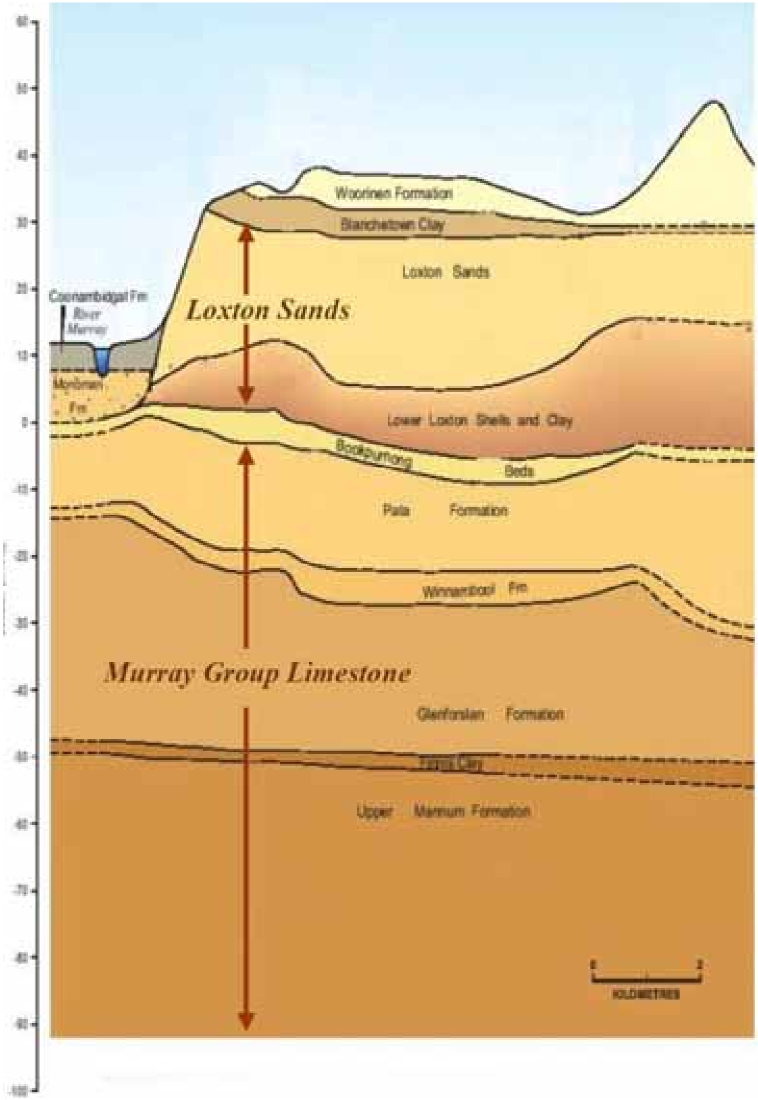

Figure 4. Hydrogeological cross-section (Yan et. al. 2005a)

The Loxton Sands aquifer forms a regionally extensive unconfined – semi-unconfined aquifer into which the channel of the ancestral River Murray is incised. Within this channel, the Monoman Formation and the overlying Coonambidgal Formation have been deposited, and it is within this sequence that the channel of the modern River Murray is incised.

Saline groundwater enters the river by lateral flow mainly from the Loxton Sands and Monomon Formation, and by slow upward leakage through the Bookpurnong Formation from the underlying regional confined Murray Group Limestone aquifer. Saline groundwater (7000–50 000 mg/L) enters the River Murray via a number of pathways:

1. Direct inflow via seepage from exposed Lower Loxton Sands at or near the base of cliffs adjacent to the river.
2. Discharge from the Monoman Formation that acts as a conduit for lateral flow from the Lower Loxton Sands and for slow upward leakage from Murray Group limestone aquifers underlying the floodplains.
3. Discharge from the Monoman Formation and localised hypersaline lakes (salinas) often at the back of the floodplain that deliver high salt loads during and after periods of flood.
4. Slow upward leakage through the Bookpurnong Formation from the underlying confined Murray Group Limestone.
5. Slow upward leakage from Murray Group Limestone that may be in direct communication with the River Murray due to erosion of the Lower Loxton Clay and Shells and Bookpurnong Formation.

These processes are summarised in a conceptual hydrogeological cross section (Fig. 5). The figure details the conceptual model of groundwater flow between the aquifers, the broader regional groundwater flow system, inter-aquifer flow and local recharge mechanisms.

The hydraulic communication between the Loxton Sands and the Monoman Formation is an important component in controlling the salt movement on the area. The flux of saline groundwater entering the River Murray is dominated by the hydraulic conductivity of the Loxton Sands, and the head difference between the river and nearby groundwater.

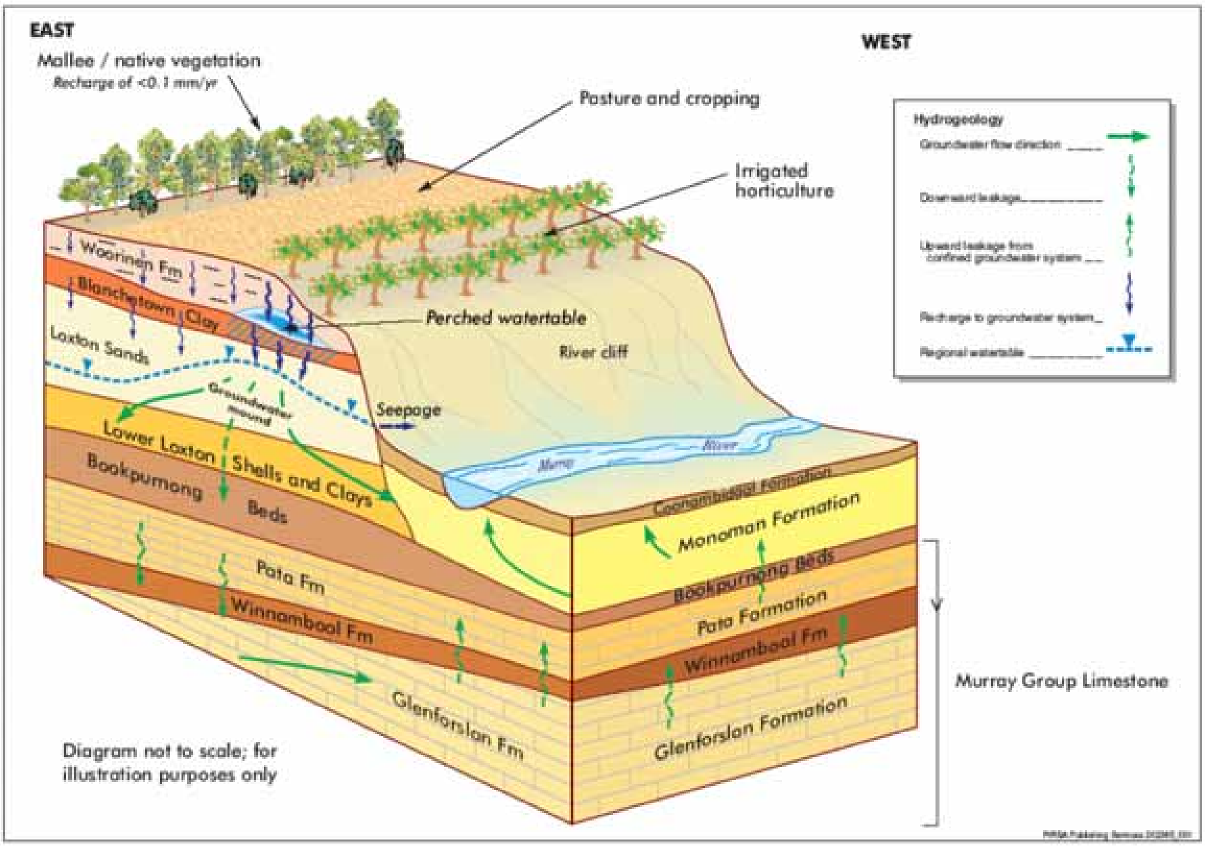

Figure 5. Elementary conceptual hydrogeological model (Yan et. al. 2005a)

Interpretation of nanoTEM data (the geophysical response to in-stream river salinity and conductivity of sediments underlying the River Murray) confirms that the majority of the flux of saline groundwater occurs in sections where the hydraulic gradients are steep (because of the groundwater mound), and where the river is in close proximity, or in contact with, the cliff faces.

As the River Murray is mainly in contact with Loxton Sands and Monoman Formation in the study area, the majority of the salt load entering the river is contributed by these two aquifers. Hence it is these aquifers that are the targets for salt interception in the Loxton area.

2.1 HYDROGEOLOGICAL UNITS

The characteristics of the hydrogeological units in the project area (Table 1) that overlie the Murray Group Limestone are discussed in order of increasing depth below ground surface.

Table 1. Hydrogeological units of the Loxton – Bookpurnong area

Hydrogeological Unit		Aquifer / Aquitard & description	Salinity Range (mg/L)	Yield (L/s)
Coonambidgal Formation		Clay layer	NA	NA
Monoman Formation		Aquifer unconfined - semi-confined in river valley	7000–60 000	0.5–10
Loxton Sand - including shell hash		Aquifer unconfined on highland	7000–40 000	0.5–5
Lower Loxton Clay and Shells		Aquitard – clay, shells	NA	NA
Bookpurnong Formation		Aquitard – clay	NA	NA
Murray Group Limestone*	Pata Formation	Aquifer (semi-confined upstream of river kilometre 486) limestone	10 000–30 000	0.5–1
	Winnambool Formation	Aquitard – marl	NA	NA
	Glenforslan Formation	Semi-confined aquifer limestone	5000–30 000	0.5–2
	Finniss Formation	Aquitard – marl	NA	NA
	Upper Mannum Formation	Confined aquifer limestone	3000–25 000	5–10
	Lower Mannum Formation	Confined aquifer limestone	NA	NA

* Not detailed in this report, see Yan et. al. 2005a

2.1.1 COONAMBIDGAL FORMATION

The Coonambidgal Formation clay layer occurs ubiquitously across the floodplain and comprises clay and silts deposited during periods of episodic flooding.

This unit is commonly 4–5 m thick in the middle of the respective floodplains, but can vary in thickness from 1–11 m, with the greater thicknesses observed at the break in slope between the floodplain and highland.

2.1.2 MONOMAN FORMATION AQUIFER

The Monoman Formation unconfined – semi-confined aquifer is the primary target for salt interception on the floodplain.

This unit consists of relatively clean, fine to coarse grained, fluvial sands deposited as point bar sands within a wide floodplain. This unit occasionally comprises minor clay and silt layers, and occasional lignite bands towards the base of section.

The Monoman Formation is commonly 4–10 m thick and is thin to absent at the break in slope. However, it can reach a thickness of up to 25 m in deep incised channels within the meander belt. As a consequence of the depositional environment, the Monoman Formation is a highly variable aquifer with yields ranging from 0.5–10 L/s. This variability makes it difficult to predict likely yields across the floodplain, to the extent that production wells separated by 10 m can demonstrate contrasting specific yields.

Due to its semi-unconfined nature, the potentiometric surface for the Monoman has been merged with the Loxton Sands (Fig. 6). Potentiometric heads are up to 2 m above river pool level (~9.8 m AHD) at the break of slope (Loxton Sands/Monoman Formation) on the eastern side of the River Murray. On the western side of the river, potentiometric heads are either close to or below river pool level with the exception of a slightly elevated potentiometric head (11 m AHD) in the area of the Katarapko Island disposal basin, to which irrigation drainage water from the Comprehensive Drainage System (CDS) network is pumped.

Groundwater salinity values in the Monoman Formation are highly variable, possibly as a result of evaporative effects on the floodplain, and range from 7000–60 000 mg/L.

2.1.3 LOXTON SANDS AQUIFER

The Loxton Sands unconfined aquifer is the primary target for salt interception on the highland, yet poses the most difficulty due to its unpredictable hydraulic nature.

Detailed sedimentological analysis, downhole geophysical logging and airborne electromagnetic (HEM) geophysical surveys (Hill et al. 2004) have helped to unravel the complexity of the Loxton Sands and provide some confidence for predicting suitable facies for salt interception close to river pool level.

The Loxton Sands generally has the most permeable coarse grained and frequently unsaturated sands occurring at the top of the sequence and the least permeable fine sands (and occasional shell hash) at the base of the succession. These sands grade to a low permeability silty clay and shell facies towards the base, referred to in this report as the Lower Loxton Clay and Shells. This upward coarsening sequence represents a shift from offshore to nearshore and back beach/dune depositional environments, reflecting cyclic eustatic sea level drops resulting in progradational clastic packages.

The Loxton Sands have been targeted in the Loxton area for salt interception where no floodplain exists. However, the base of the fine sands and shell hash occurs close to river pool level and accordingly, this has a significant impact on production well spacing in order to achieve effective salt interception. Although the Loxton Sands are commonly up to 25–30 m

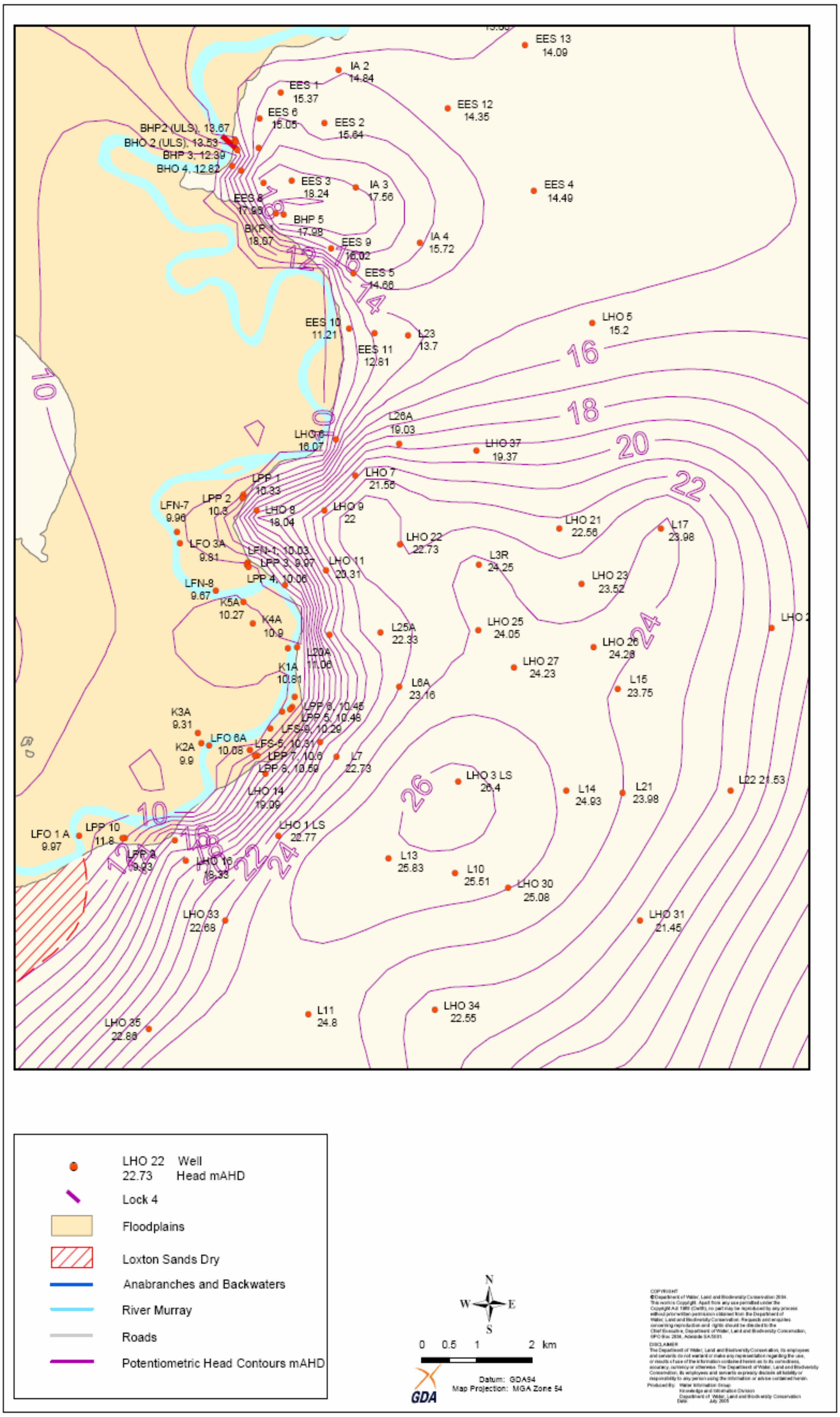

Figure 6. Loxton Sands and Monoman Formation potentiometric surface May 2004 (Yan et. al. 2005a)

thick, the permeable basal shell hash and coarse sand unit that occur at the base of the succession in the Loxton area is only 2–3 m thick. Yields up to 1.5 L/s have been observed in production wells completed in the basal shell hash facies. Elsewhere, yields vary from <0.5 L/s in fine-grained sands up to 5 L/s in coarse-grained facies in the area targeted for highland interception in the Bookpurnong area.

The potentiometric surface for the Loxton Sands and Monoman Formation for May 2004 is given in Figure 6. A prominent groundwater mound trending northeast - southwest occurs in the Loxton Sands in the Loxton irrigation area with a maximum height of 26 m AHD, and a smaller mound occurs in the Bookpurnong area.

Groundwater salinity values in the Loxton Sands vary dramatically across the Loxton – Bookpurnong region, reflecting impact of low salinity irrigation recharge on the saline native groundwater. Groundwater salinity data were sourced from pumping tests and HYDROLAB geophysical sonding, the latter demonstrating stratification with the heavier dense saline groundwater underlying fresher irrigation water. For the purposes of predicting salt loads entering the River Murray, the more saline native groundwater values were adopted for various zones along the river ranging from ~5000–40 000 mg/L.

2.1.4 BOOKPURNONG FORMATION

The Bookpurnong Formation aquitard occurs between the Loxton Sands aquifer and the underlying Pata Formation. This unit consists of poorly consolidated plastic silts and shelly clays that are differentiated from the Lower Loxton Clays and Shells (grey in colour) on the basis of colour (light to dark khaki) and increased plasticity.

The Bookpurnong Formation reaches a maximum thickness of 15 m in the Loxton area but is highly variable with no discernable trend observed. This unit is thin to occasionally absent on all floodplains in the Loxton area more likely as a consequence of erosion but possibly as a result of depositional thinning.

3. PRELIMINARY INVESTIGATIONS

During preliminary investigations for the Loxton SIS, it became apparent that on the highland areas (where there is no floodplain adjacent the River Murray) the most permeable sands occur above 10 m AHD with an observed decrease in permeability and porosity with depth. The poorest aquifer sands tend to occur near river pool level (9.8 m AHD) in the Loxton reach.

Preliminary investigation drilling pinpointed a thin but persistent unit, comprising poorly sorted sands and reworked shell material (commonly called 'shell hash'), up to 2 m in thickness. This unit is continuous for at least 700 m in places, and occurs at depths of 18–24 m below natural surface (close to river pool level) depending on topography (Fig. 7). The unit is overlain by silts and upward coarsening sands of the Loxton Sands, and directly overlies the Lower Loxton shells and clays.

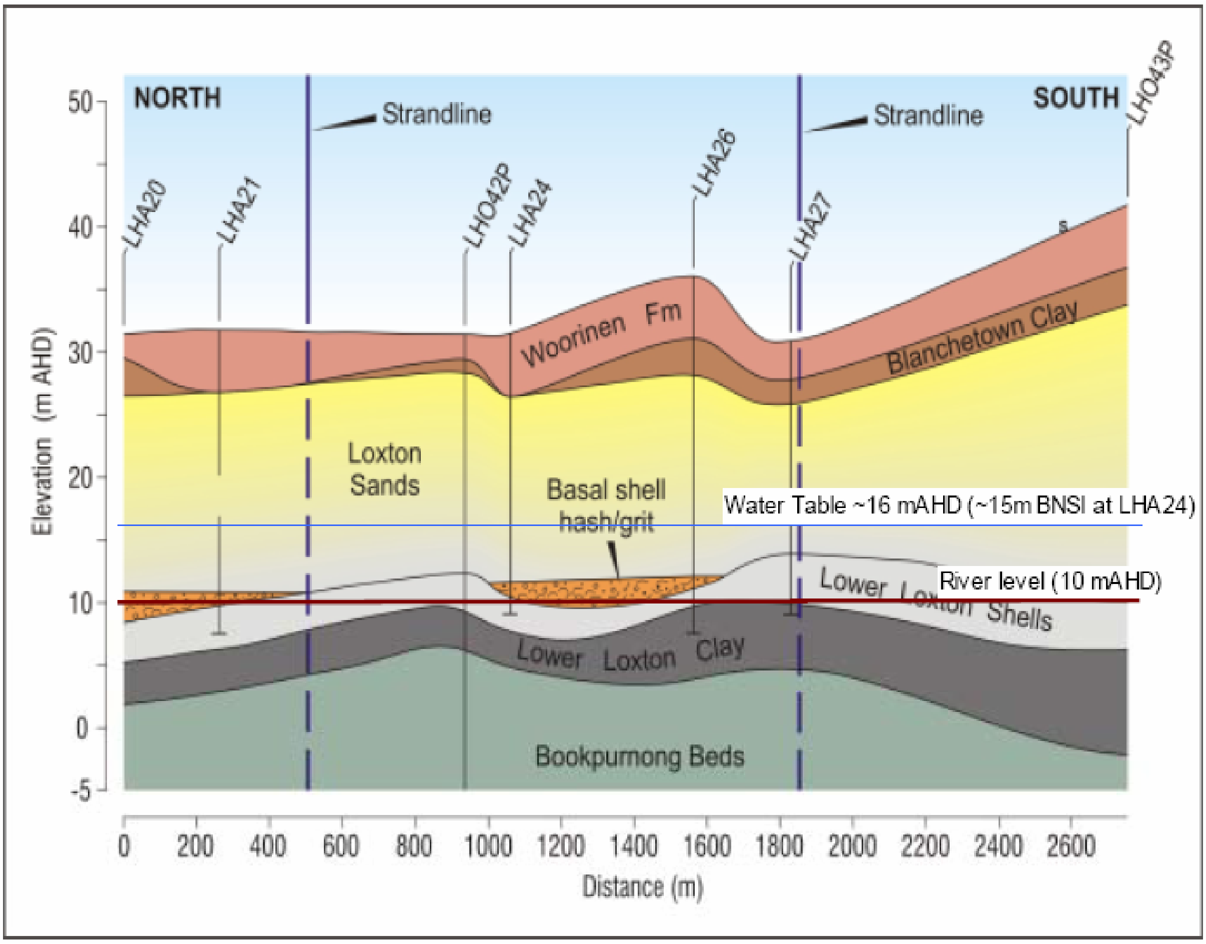

Figure 7. Hydrogeological cross-section along line of trial horizontal drainage well

A number of investigation air-core drill holes (refer App. A) were drilled to assist in identifying the presence and characteristics of the target shell hash unit in the area of the trial horizontal drainage well (Fig. 8). In addition, two production wells and associated observation wells were drilled.

The groundwater table occurs 15–20 m below the natural surface. Pumping tests indicated that the shell hash had reasonable yields, up to 3 L/s. However, the unconfined and thin nature of the aquifer (that includes the shell hash and the overlying saturated sands) would result in the need for very closely spaced conventional vertical wells to achieve interception, which would be limited by the practical drawdown that could be developed (Howles and Smith, 2005).

Another alternative, eductor wells (wells operating at low pumping rates and driven by compressed air), would need to be drilled at a spacing down to perhaps 2 m, which would result in significant cost.

A horizontal drainage well would provide a significantly better and simpler interception option than either of the preceding alternatives.

Prior to commencing the project, additional investigation drilling (refer App. A) was undertaken to confirm the geological sequence. Some of these investigation drill holes were completed as observation wells in the shell hash in five transects perpendicular to the line of the trial horizontal drainage well. Each transect included observation wells located at a distances of ~5 m and ~20 m from the trial horizontal drainage well (Fig. 8).

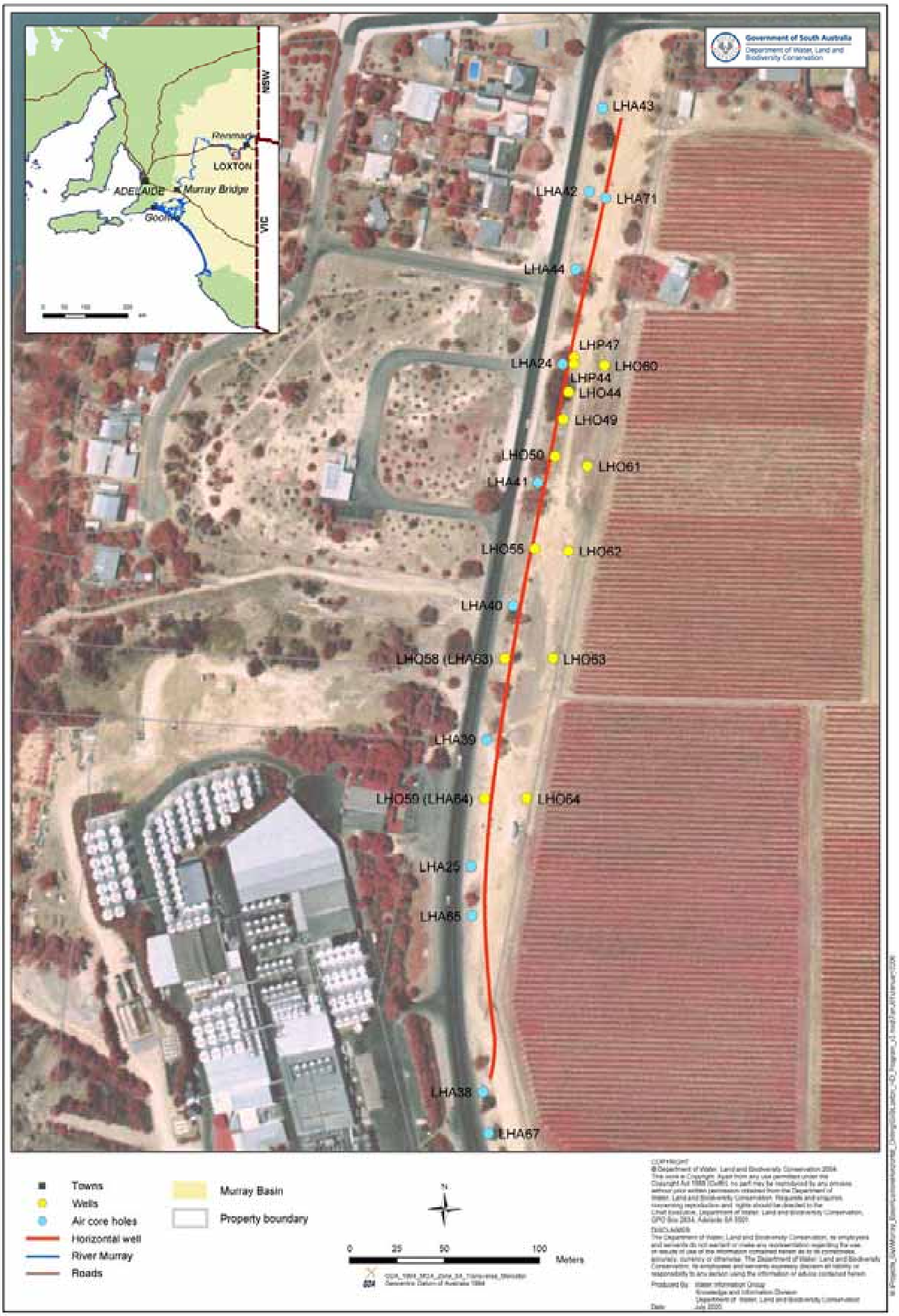

Figure 8. Location of trial horizontal drainage well

4. DESIGN AND CONSTRUCTION

4.1 HORIZONTAL DIRECTIONAL DRILLING

Horizontal directional drilling (HDD) was initially developed to assist the petroleum industry target hydrocarbon deposits that would otherwise be too costly or environmentally disruptive to access. During the 1970s, this same technology was adapted to road crossings and underground boring situations. Today HDD is more widely used, and the technology makes it possible to install a pipeline or utility directly below virtually any obstacle. Increasing environmental and safety concerns make HDD the best, and often the only, technique for installing utilities below waterways, fragile environments, and the dense urban development.

The application of HDD for the construction of a trial horizontal drainage well for salt interception is an entirely new application of this technology within Australia.

HDD incorporates the mud rotary drilling system. The principle common to all rotary-drilling techniques is that a drill bit is attached to the end of a hollow drill pipe and rotated against the bottom of the hole. Pressure is applied to the bit by the weight of the drill pipe and additional weight (feed) is then applied from the drill plant. The cuttings produced during drilling are cleared by continuously circulating drilling fluid (or mud), derived from tanks near the rig, which is pumped down through the drill pipe emerging through nozzles in the drill bit. The fluid then flows upward in the annular space around the drill pipe to the surface, carrying the cuttings in suspension. At the surface, the fluid is firstly channelled into a settling pit, where most of the cuttings settle out, and then into a storage pit, where it is pumped back into the drill hole.

The rotary drilling system was developed for dealing with soft, unconsolidated formations that would otherwise collapse. The drilling fluid forms an impermeable membrane that inhibits flow through the walls of the drill hole, provides structural support to the drill hole, and serves to cool and lubricate the drill bit.

During the drilling of a horizontal drill hole, it is desirable that continuous geophysical logging (i.e. gamma log) be undertaken to more accurately inform the onsite hydrogeologist of any subtle lithological changes. Before commencement of drilling of the pilot drill hole in the current project, the gamma sensor was inverted (from its usual position to detect clay above the drill-string) to aid in detecting the Lower Loxton Clays underlying the shell hash. However the sensor was not successful in this application due to the nature of the Lower Loxton Clays.

4.2 THE CONTRACTOR

A J Lucas Group Limited (based in Sydney) won the contract for the drilling of the trial horizontal drainage well. Lucas is an infrastructure technology company providing outsourced services to the energy, water and telecommunications industries in Australia and Asia-Pacific. Founded in Sydney in the 1950s, today Lucas' activities involve works in the engineering field and construction of utility infrastructure (gas, oil and electricity distribution, water and sewerage systems and telecommunications networks).

During the tender phase of the project professional advice was sought from Mr Blair Mitchell of HDD Consult Pty Ltd [http://www.hdd-consult.com]. Mr Mitchell provided advice on HDD, drilling contractors, and valuable on site supervision several times during the drilling of the trial horizontal drainage well.

4.3 WELL DESIGN

Lucas recommended that the product pipe should be high-density polyethylene (HDPE). This material is more versatility in its strength and more cost effective than either polyvinylchloride (PVC) or stainless steel alternatives.

Due to the reasonably consolidated nature of the shell hash (indicated from investigation drilling) it was originally intended that the trial horizontal drainage well would be completed with a single string of HDPE pipe slotted longitudinally (to minimise loss of pipe strength) with 10 rows of 200 mm external length (150 mm internal length resulting from the cutting of the slots with a circular saw blade) x 2 mm wide slots (configuration given in Fig. 9a) resulting in an open area of ~1%.

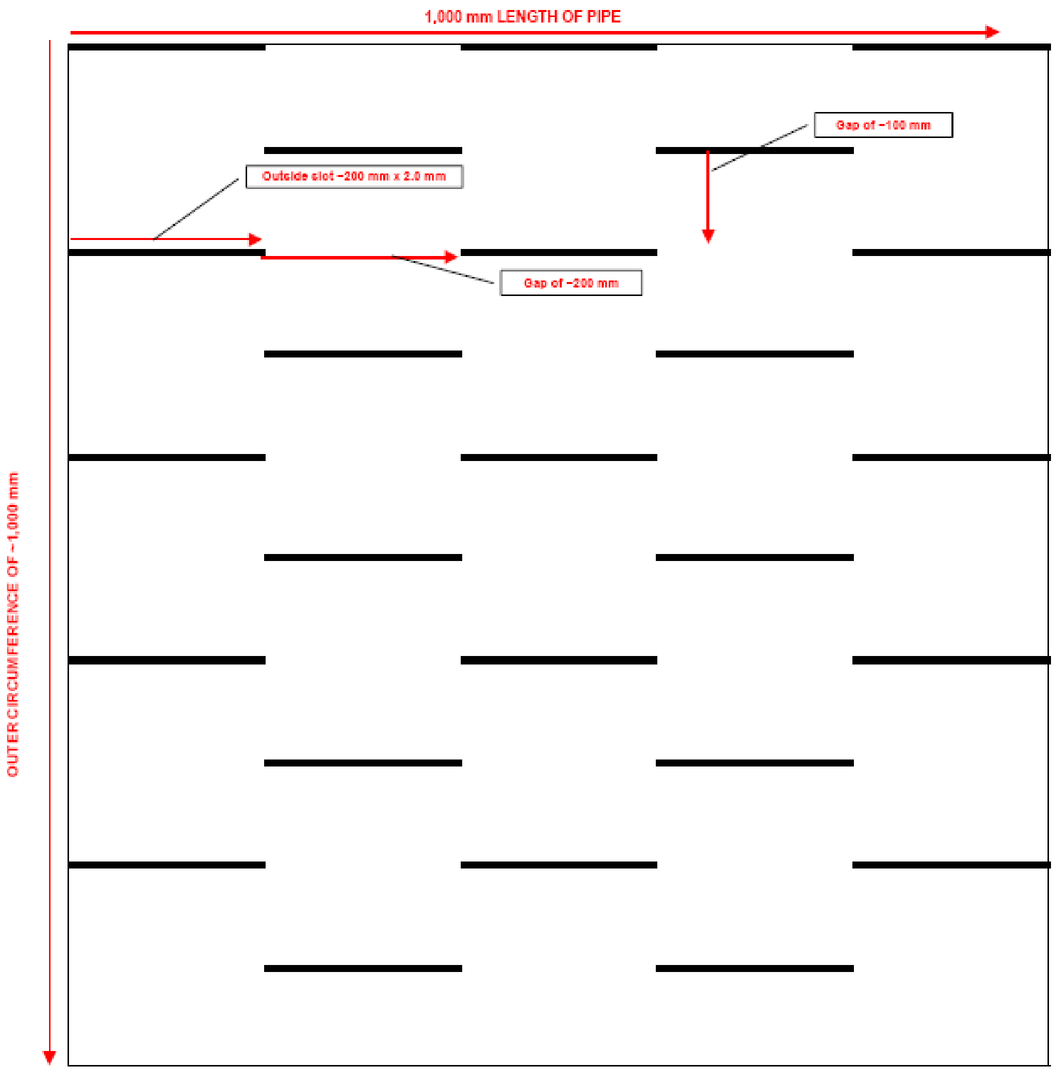

Figure 9a. Outer product pipe original outside slot configuration

Lucas determined that the slotting configuration would result in sufficient strength remaining in the product pipe (wall thickness 35 mm) to withstand the pulling and frictional forces that would be experienced during pullback (the process of pulling the product pipe back through the drill hole).

Within days of slotting the first section of product pipe it was noticed that slots had begun to close from either side and form a double concave like slot, and the slotting was terminated after ~50 m of the pipe had been slotted. After further investigation and research it was discovered that all thermoplastic pipes have 'frozen in stresses', which have their origin in the cooling phase of the manufacturing process. Cutting the pipe can result in movement that is known as 'reversion'.

It was subsequently concluded that spherical holes would tend to maintain their integrity and remain open. This resulted in a last minute decision to replace the slots with ten rows of 10 mm diameter drill holes spaced at 75 mm centres (configuration given in Fig. 9b) resulting in an open area of 1% (the lengths of pipe that had been slotted were over drilled with 5 rows of drill holes as it was assumed that some of the slots would remain open).

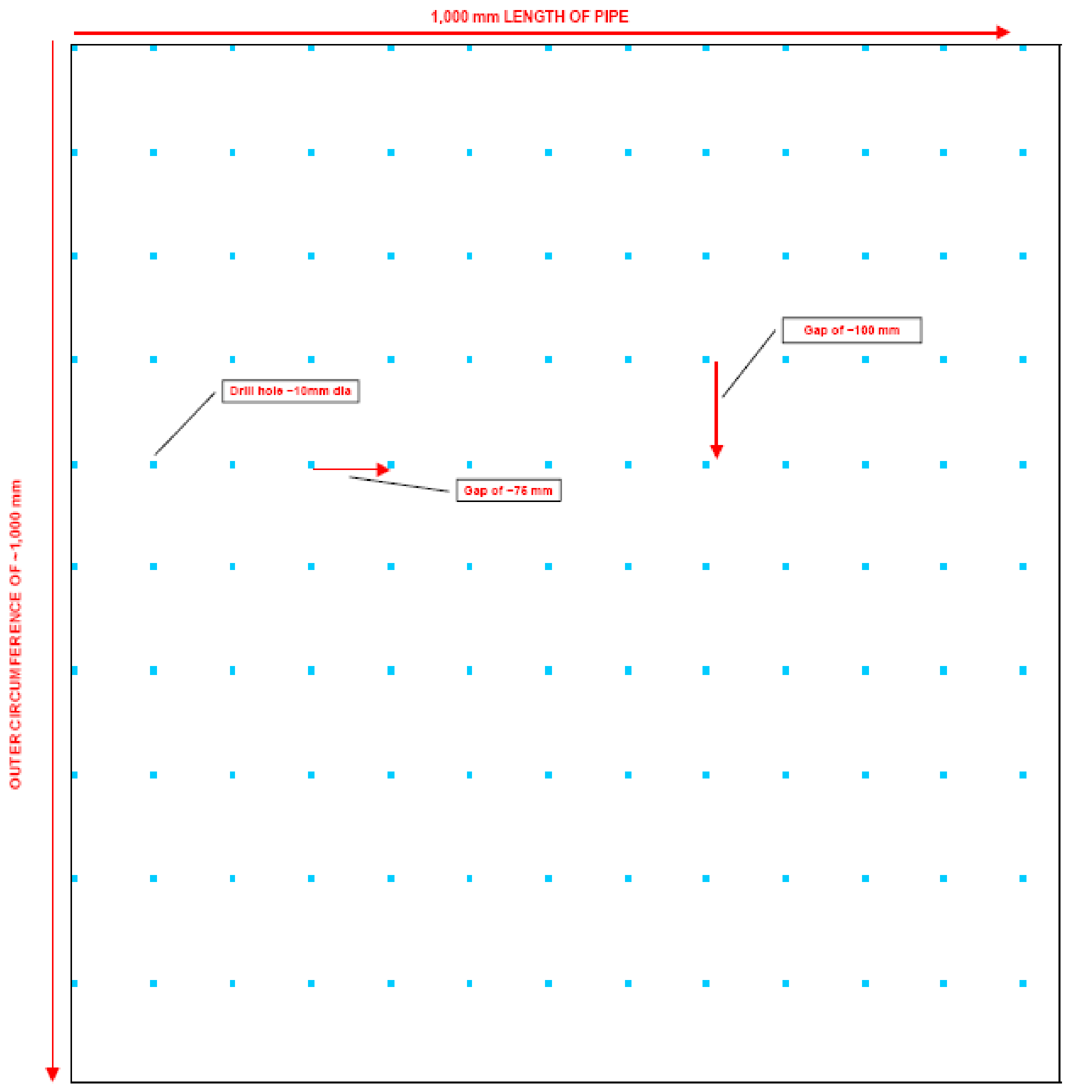

Figure 9b. Outer product pipe drill hole configuration

At the anticipated maximum discharge rate of 15 L/s a 1% open area results in an entrance velocity of the order of 0.014 m/s, which is considerably less than the nominal maximum value of 0.03 m/s normally recommended for well screens (at a discharge rate of 7 L/s this reduces to 0.007 m/s).

Concerns regarding the potential ingress of material through the drill holes were addressed by coupling the outer product pipe (Fig. 10) with an inner thin walled HDPE liner slotted radially (Fig. 11) with one row of 100 mm long x 0.8 mm wide slots cut at 20 mm spacing down each side of the pipe.

Figure 10. Outer product pipe drill holes

Figure 11. Inner liner slots

The inner and outer product pipe specifications are given in Table 2. All slotting/drilling, fusion welding, and de-beading was conducted by Mr Mick Jagger of Complete Pipe Systems (Callington, South Australia).

Table 2. HDPE pipe specifications

Specifications	Outer Product Pipe	Inner Liner
Material	SDR9 HDPE PE100	SDR9 HDPE PE100
Pipe Joints	Fusion welded, de-beaded inside/ outside	Fusion welded, de-beaded inside only
Outer Diameter	315 mm	220 mm
Inner Diameter	245 mm	210 mm
Wall Thickness	35 mm	5 mm
Slotting Orientation	Longitudinal	Radial
Slot Length	NA	100
Slot Width	2 mm, replaced with drill holes	0.8 mm set 20 mm apart
Slotted length	270 m	270 m
Drill hole diameter	10 mm	N/A

HDPE – High density polyethylene

4.4 DRILLING AND WELL CONSTRUCTION

In July 2005 drilling of the trial horizontal drainage well commenced at the investigation site approximately 10 km north of the township of Loxton (Fig. 8).

Drilling the trial horizontal drainage well required three distinct construction phases:

1. Drilling the pilot hole.
2. Reaming.
3. Pulling of product pipe.

In addition to the drilling rig (refer App. B for specifications of the size and type of rig used) a variety of support equipment was required:

- A drilling fluid conditioning and recirculating unit.
- A water truck with appropriate pumps and hoses.

The following important issues were considered prior to the commencement of drilling:

1. Sufficient room in the workspace environment for excavation at the entry/exit points and siting of drilling fluid recirculation pits.
2. The drilling fluid containment and disposal plan.
3. A contingency plan for recycling drilling fluid.
4. A disposal plan for (saline) groundwater produced during development. It was anticipated that development using the drilling rig may extend for several days and be followed by a long period of pumping to fully clear drilling fluids from the well.
5. The most suitable drilling fluid.

4.4.1 DRILLING FLUID

The role of the drilling fluid in mud rotary drilling is to stabilise the hole during drilling, facilitate the removal of formation cuttings, and act as a lubricant and cooling agent for the drill bit. In HDD, the drilling fluid also reduces friction within the drill hole thus lowering the force required to successfully complete the installation of the product pipe.

The drilling fluid demands of HDD are different from those required for the drilling of conventional vertical wells. Gel strength (the ability of the fluid to suspend material) is much more important for horizontal drilling, where lower viscosity and high gel strength are required to suspend the cuttings in the drilling fluid.

The base fluid normally used for rotary drilling is water, to which specific chemicals and other additives can be added to increase viscosity, and to improve drill hole support. Drilling fluid properties are maintained within the limits that will allow their complete removal from the well, and are not to affect the potential capacity, efficiency, or quality of the well. Bentonite is a commonly used additive, as it has the strength to maintain the integrity of the drill hole, and has a strong carrying potential (gel strength).

Following the drilling of conventional vertical wells, development removes the drilling fluid from the screened interval. It was anticipated that the development would be considerably less effective for the horizontal drainage well due to the small open area, and as a consequence the type of drilling fluid to be used would be critical. The drilling fluid must form a minimum wall cake and be readily removable through development following the well completion.

Professional advice was sought from Mr Kerry Booth of the Australian Mud Company Ltd [http://www.ausmud.com]. It was his recommendation that the naturally occurring biodegradable polymer, Xanthan Gum (Fig. 12), be used. This is a product that is derived from the sap of trees grown in India.

Figure 12. Xanthan Gum - polymer used as drilling fluid

Xanthan Gum rapidly degrades in the environment under attack from naturally occurring bacteria, hence biocide was added to the drilling fluid on a daily basis during the drilling of the trial horizontal drainage well, to inhibit premature degradation. Drilling fluid properties were also maintained within the specified limits using standard test procedures, e.g.:

1. Fluid density — test equipment: mud balance.
2. Viscosity — test equipment: Marsh funnel.
3. Filtration (wall cake and filtration loss) — test equipment: filter press.
4. Sand content (solids larger than 200 mesh) — test equipment: sand-content set.

4.4.2 PILOT DRILL HOLE

Drilling of the trial horizontal drainage well (Permit Number 107837) commenced on 7 July 2005 with the drilling of the pilot drill hole (Fig. 13). The pilot hole is the most critical part of the horizontal drilling process, as it determines the position of the final drill hole.

Figure 13. Commencement of pilot drill hole with blade bit

Once the path of the pilot drill hole had been designed and plotted digitally, the pilot drill hole commenced using a drill bit that had a weighted bias to give the directional control needed to follow the proposed path.

The drilling target was a 1–2 m thick sequence of reasonably consolidated shell hash. In order to successfully complete the pilot drill hole, the drill bit had to be accurately steered through this interval, preferably intersecting the unit as close to the base as possible, without penetrating the underlying clay unit.

The pilot drill hole commenced at an initial entry angle of approximately 14 degrees with a blade bit capable of cutting a 170 mm diameter hole. The pilot drill hole proceeded at a reducing angle for approximately 110 m, where upon approaching the target formation the angle reduced to approximately 0 degrees for the start of the horizontal section. The target formation was then followed for a total horizontal distance of approximately 240 m. However it must be noted that three fifths of the way through the horizontal section a decision was made to change from a blade bit to a mud motor (which results in a hydraulically driven, faster rotating, drill bit) and tri-cone bit more suitable for harder formations. This required full retraction of the drill bit away from the cutting face and removal of drill-string. The mud motor was then attached to the drill-string, the pilot drill hole re-entered, and the bit navigated along the pilot drill hole to the cutting face. Once at the cutting face, the horizontal section of the pilot drill hole was completed. At this point the mud motor was continued upwards towards the natural surface reaching a maximum exist angle of approximately 11 degrees. A comprehensive cross-section utilising the data from all the investigation drill holes, also showing the elevation of the pilot drill hole, is given in Figure 14.

Aside: Drilling fluid circulation:

Once the exit point is reached, the drilling fluid circulation system becomes more complex, as the additional component of flow to the surface at the exit point, must be returned to the drilling rig. At the trial site, this component of drilling fluid was pumped back to the drilling rig through a steel pipe return line. Solids settling out in the return line actually prevented flow, and resulted in the need to truck drilling fluid between the exit and entry points of the drill hole. Drilling fluid return may have been better facilitated using a second fluid-cleaning unit at the exit point to clean the fluid before returning it to the rig. In addition, a sand content reducer may be required at the exit point. Further, the pump intake needs to be set well below the drilling fluid level in the holding pit to prevent air entering the return line.

4.4.3 REAMING

Following the completion of the pilot drill hole, the drill bit and mud motor were removed and replaced with a ring style reamer and trailing drill rods with a capped end (Fig. 15). This phase entailed reaming the pilot drill hole to a diameter large enough to accommodate the outer product pipe. After initiating drilling fluid return to the rig, reaming commenced at the exit point, where the reaming tool was dragged back through the pilot drill hole towards the drilling rig. This was a reasonably simple process of removing rods at the rig, and adding them onto the trailing rods at the exit point. Once the reaming tool had traversed the length of the pilot drill hole, a barrel style reamer was used to both clear and prove the hole, ready for pullback of the outer product pipe.

4.4.4 OUTER PRODUCT PIPE PULLBACK

The outer product pipe was fusion-welded into a single continuous string, de-beaded inside and outside, laid onto rollers, and pulled into place through the reamed hole by connecting it to the end of the drill-string. To withstand the pullback, the pipe must be of sufficient strength (including a safety factor following slotting/drilling) to withstand the pulling force and the friction.

In order to facilitate pullback, a barrel reamer/pig was attached to the drill string to prevent drill hole cave-in (note that the leading edge should be sealed to prevent scour of formation material [and the pipe filled with to prevent floating]). An articulated joint (or swivel) was attached between the pig and the product pipe to ensure that the rotational torque from the drill-string did not spin the pipe during pullback (Fig. 16).

The outer product pipe pullback took five hours.

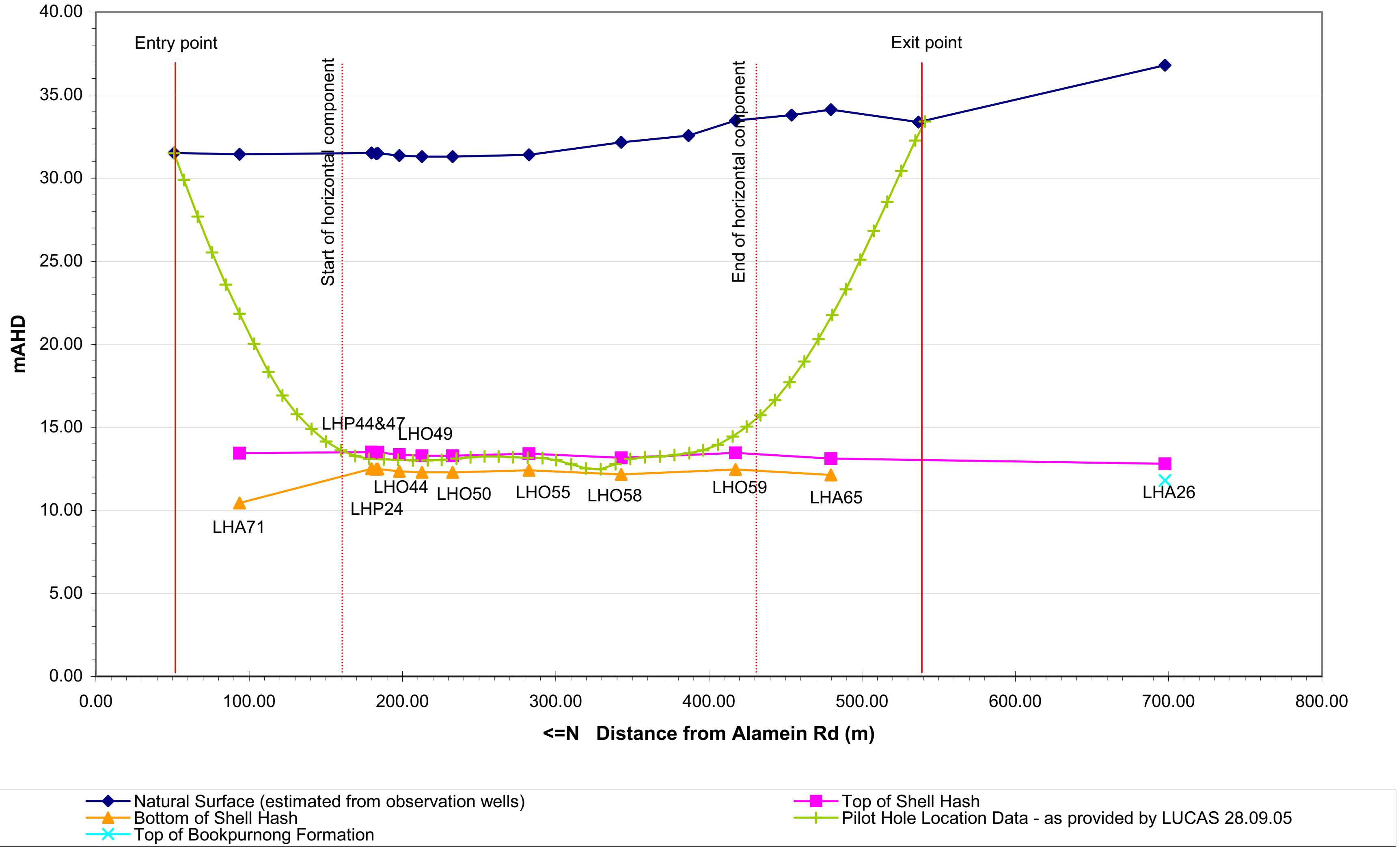

Figure 14. Aquifer geometry and plot of pilot drill hole profile

Figure 15. Commencement of reaming

Figure 16. Commencement of pullback

4.4.5 DEVELOPMENT

Development is designed to bring a well to its maximum production capacity by optimising the well specific capacity and stabilising aquifer material. The conventional approach of jetting, surging and airlifting was not expected to be effective for the trial horizontal drainage well due to its design. The effectiveness of jetting on the very small open area of the outer product pipe was questionable, while there was concern that air-lifting may actually reduce the efficiency if air became trapped behind the pipe.

Initial development was conducted over a five-day period using a combination of chlorine and mechanical agitation to further breakdown the biodegradable polymer used in the drilling process. Development commenced from the southern end (exit point) of the trial horizontal drainage well where a development 'pig' was attached to the drill-sting (Fig. 17). Drilling fluid and groundwater produced during development was trucked away for disposal using a tanker as required. This occurred several times during the course of development.

Figure 17. Development pig attached to drill string

The pig had the ability to swab the hole (using the polypropylene rings) and jet (using the six holes exposed between the rings). The drill-string was pulled back until the pig rested adjacent to the drilled (screen) section and jetted with a combination of water and chlorine to accelerate the break down of the drilling fluid. Jetting ceased when the pig passed the screen section of the pipe. Three additional passes were conducted with the pig but without jetting. On the final (fifth) pass, two polyethylene rope lines were attached to the pig to allow for the inner liner pullback.

Each pass revealed some sediment, quantities decreasing with each pass, and groundwater with a colour similar to that of the drilling fluid. At this point it was accepted that the trial horizontal drainage well was reasonably free of sediment.

Due to the prohibitively high cost of retaining the rig on site (Australian $30 000/day), it was decided that additional development would have to be undertaken following the installation of the pumps. Further development was subsequently undertaken by pumping and this will be reported separately with the results of the initial hydraulic testing.

4.4.6 INNER LINER PULLBACK

The inner liner was fusion-welded into a single continuous string, de-beaded inside only, laid onto rollers, and winched into place through the outer product pipe. The thin wall of the pipe, cooled rapidly after being welded and this complicated debeading. A number of trials were undertaken to perfect the process. De-beading needs to be undertaken as quickly as possible.

The inner liner pullback took one and a half days.

The leading end of the inner liner (i.e. the un-slotted section) should have been sealed to prevent scouring of formation material sitting within the outer product pipe into the inner liner.

This would also require the lead end of the pipe to be filled with water to prevent it floating (thus making the pullback more difficult).

Following pullback of the inner liner, a pig was pulled through the inner liner (by attaching it to a conventional automatic vehicle) to ensure the inner liner was fully open. The pig produced less than 250 mL of sediment.

4.4.7 HEADWORKS

An internal cable was placed in the trial horizontal drainage well to enable pulling of various equipment through the well at a later date. The outer product pipe, where exposed at surface, was fitted with steel caps fabricated and fitted by SA Water (Fig. 18).

Figure 18. Outer product pipe fitted with steel end cap

4.4.8 REMEDIATION OF DRILLING SITE

On completion of the work, the contractor ensured that drilling fluid, and other fluids used in constructing the trial horizontal drainage well were disposed of in accordance with Environmental Protection Agency (EPA) regulations. Drilling fluid pits were drained and backfilled, and the site was graded and restored to the original condition.

5. TECHNICAL ISSUES

5.1 HDD STEERING TOOLS

It is critical to know where the drill bit is located at any particular point in time. There are two separate systems commonly used in horizontal drilling for locating the drill bit:

1. Walk over system.
2. A transmitter (also referred to as a beacon or sonde, Fig. 19).

For this project Lucas used both a 'gyroscope survey transmitter' coupled with the 'Tru-Tracker' system, for calibration at the entry and exit points.

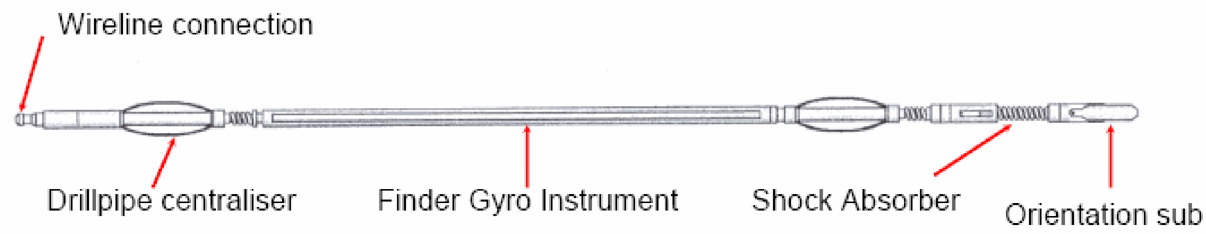

Figure 19. Gyroscopic survey tool

5.1.1 GYROSCOPE SURVEYING

The transmitter was placed in the housing located behind the drill bit, and from there it sent a signal back to a receiver located in the rig steering box. Software was used to plot the progress of the drill bit underground.

The Finder Gyroscopic Survey Tool from Scientific Drilling Limited is a development of a north seeking 'Rate' gyro survey system (Lucas, 2005). The instrument has several different modes of operation, however for this application surveying was undertaken in a roll stabilized inertial navigation mode. A known azimuth is used as the initial reference. Following setup of the tool to read this known azimuth, the gyro is drift tuned to eliminate drift related azimuth errors. It can then be run over the required interval, giving a constant printout of the survey information over that section, as well as a continuous stream of quality assurance information. While surveying, the gyro input axis is kept vertical by stabilizing sensors. As the finder surveys over the required interval, any changes about this input axis (caused by a change in drill hole direction) are measured in degrees and referenced back to the initialization azimuth. While drilling, the system operates in steering mode, which gives a continuous high side tool face reference. In this mode the tools accelerometers are used as the principal measurement sensor while the gyro is used in a stabilized role.

5.1.2 TRU-TRACKER

The Tru-Tracker system (Fig. 20) is primarily a guidance system used for calibration of the transmitter particularly upon entry and exit of the constructed drill hole. This system vastly improves the accuracy of the steering tools (Lucas, 2005).

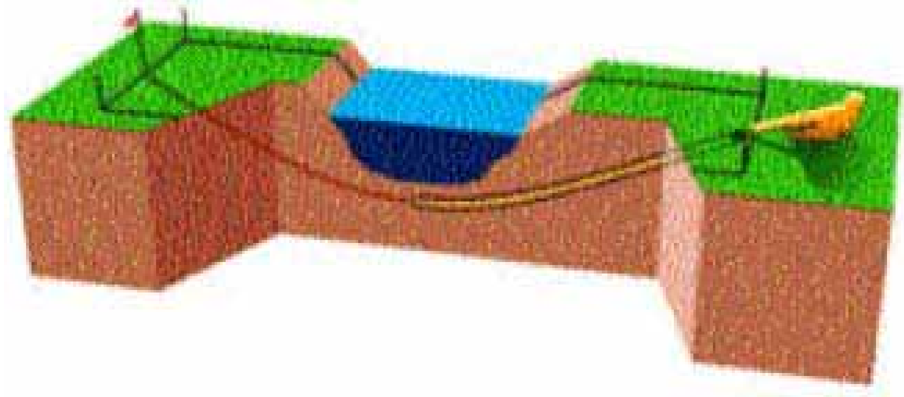

Figure 20. Tru-Tracker system grid layout

Tru-Tracker involves laying cables on the ground surface along the route of the proposed hole. This is generally only possible near the entry and exit point of the drill hole due to depth limitations of this technique. These cables are accurately surveyed relative to the entry point and proposed drill profile line. Once these cables are laid out and surveyed they are then energized with a low strength direct current, which induces a magnetic field of known characteristics. Such an imposed magnetic field removes reliance of the steering tool on the earth's magnetic field. The influence of this induced magnetic field upon the magnetometers may be calculated and analysed via computer using complex tensor mathematical models. The position of the steering tool can then be accurately determined within the confines of the surveyed cable grid. This secondary and completely independent survey technique is highly accurate and negates the effect of any magnetic anomalies that may be present in the vicinity of the proposed drill hole. Tru-Tracker ensures the correct alignment of the pilot drill hole.

5.2 HDPE PIPE

HDPE is the high-density version of polyethylene (PE) plastic. It is lighter than water, and can be moulded, machined, and joined by fusion welding. The appearance is wax-like, lustreless and opaque. The use of UV-stabilisers (carbon black) improves its weather resistance.

The cooling of the extruded pipe normally takes place externally in a water bath, resulting in bending stresses in the pipe walls. These stresses arise in the following manner. During cooling the external surface layer contracts thermally, while simultaneously the still warm surface layer on the inside of the pipe compresses plastically. When the inside subsequently cools, its surface layer endeavours to contract as a consequence of the thermal change in length, but is prevented from doing so by the external surface layer which has cooled sooner and already assumed its form. As a result, the inside is subject to tensile stresses and the outside to compressive stresses. The faster the cooling and the greater the material thickness, the more severe the bending stresses. If a pipe is cut in the longitudinal direction, this will cause a reduction in its periphery thereby providing a direct measurement of stress magnitude. This change is known as ‘reversion’.

The frozen-in stress is estimated, assuming a triangular distribution of the stresses in the pipe wall, and the pipe in this case being regarded for the sake of simplicity as a thin elastic ring. It is further assumed that the deformations are small in relation to the pipe diameter. Thus, an overlapping at the rupture or, more accurately expressed, a reduction (a) of the pipe periphery, when it is cut free from stress, corresponds to a bending stress in the un-ruptured pipe of (Janson, 2003):

$$\sigma = \frac{a}{(\pi D_m - a)}(\frac{s}{D_m})E$$

where

σ = bending stress in pipe

a = reduction of the pipe periphery

E = the bi-axial creep or relaxation modulus of the pipe material

s = the thickness of the pipe wall

D_m = the mean diameter of the pipe = D–s

D = the external diameter of the pipe

The reversion issue should be considered prior to the drilling of further horizontal drainage wells.

6. CONTRACTUAL ISSUES AND FUTURE AMENDMENTS

6.1 THE CONTRACT

The successful construction of the trial horizontal drainage well was dependent on a robust well design and clearly defined contract and technical specification. The following points were key issues in the success of the drilling contract:

1. The passing of the risk regarding Latent Conditions to the contractor by replacing the detailed section in the standard Drilling Contract with a simple statement reading “the contractor must form his own opinion regarding site conditions”. Due to the amount of geotechnical information that had been collected during preliminary investigations this was considered to be a reasonable risk to pass to the contractor.
2. Ensuring the contractor bore the cost of a ‘Lost Well’ in full by clearly stating that the large mobilisation and site establishment fee, that was paid up front, was to be reimbursed to DWLBC in full (except for the cost of the product pipe and its slotting/drilling). To further ensure this would occur, a security bond of 5% of the total contract price was required from the contractor that would be reimbursed once the mobilisation and site establishment fee had been reimbursed to the DWLBC.
3. A defects liability period of 12 months on the trial horizontal drainage well (excluding the mechanical integrity of the outer product pipe which had been compromised by slotting/drilling, but including the fusion welded joints) commenced from the date of completion. It should be noted that it would be unlikely that anything could go wrong with the well. In future contracts it should be stated that the risk to the well from infiltrating sands lies with DWLBC, as the contractor cannot be held responsible for risk in well design, or a well that is not fully developed.

6.2 PROPOSED AMENDMENTS TO FUTURE TENDERS AND CONTRACTS

The administration of the contract resulted in the highlighting of a number of additional issues that should be clearly addressed in future tenders and contracts, i.e.:

1. Note that, in theory, points (1) and (2) above would ensure that there was no financial risk to DWLBC if the project was unsuccessful. However, this assumes that there would be no argument regarding the calling of a Lost Well by the DWLBC; and that even if a lost well was accepted by the contractor, that the mobilisation and site establishment fee would be reimbursed without question. Future contracts should address this by ensuring that the security bond is equal to the mobilisation and establishment fee.
2. The contractor must provide clear information and personnel profiles, including for any sub-contractor or hired personnel in the tender, and this information must be included in the contract.

3. The decision regarding the nature of the outer product pipe must lie solely with the contractor. The contractor must ensure that the thickness of the outer product pipe wall is sufficient to accommodate the slotting/drilling and still allow the pipe to be pulled into position.
4. The contractor must carry out a topographical survey and generate a proposed pilot drill hole profile prior to the commencement of the pilot hole. This profile must include the alignment and depth of the pilot drill hole, together with the entry angle and bend radius of drill string. This profile must meet the approval of DWLBC and be included in the contractor’s final report.
5. The contractor must carry out a site inspection to determine any potential hazards (e.g. electromagnetic radiation from power cables), which may affect the resolution of the steering tools. These risks need to be passed to the contractor and defined in the contract.
6. The contractor must use a minimum of a ‘wire-line gyroscope survey transmitter’ steering system coupled with the ‘Tru-Tracker system’ to enable accurate and positive location of the drill bit at all times throughout the drilling operation. This log must be included in the contractor’s final report.
7. The contractor must provide details of the ‘wire-line gyroscope survey transmitter‘ steering system coupled with the ‘Tru-Tracker system’ that will be used to determine the downhole location of the drill bit, their technical specifications, their accuracy, whether they will be affected by surrounding services (e.g. power lines) and to what extent. The specification of the tools must be defined in the contract.
8. The contractor must drill the pilot drill hole with continuous monitoring of the information detailed in the Drill Hole Log Requirements, Reaming Log Requirements, and Product Pullback Log Requirements (App. C). This log must be included in the contractor’s final report.
9. The contractor must monitor drilling fluid properties (including viscosity, sand content and ratios/quantities of additives) throughout the entire drilling of the horizontal well. This information must be included in the contractor’s final report.
10. The contractor must drill the pilot drill hole such that the drill bit remains within the agreed elevation corridor, and if an excursion occurs the drill bit must be retracted to a point where the drilling can recommence and provide correction. No payment should be made for lost time or any other expenses incurred in relation to retracting the drill bit and advancing it to the point from which retraction occurred. All such manoeuvring must be defined and reported in the contractor’s final report.
11. The contractor must provide the Wellsite Hydrogeologist with a ‘true vertical depth’ and ‘total hole length’ at the end of every drill rod during the drilling of the pilot drill hole.
12. An independent surveyor must be contracted by DWLBC to determine the entry and exit ground coordinates and elevations of the final completed well by two independent surveys. These surveyed values should correspond with the values provided by the contractor, and if not, the contractor must establish the final well position and profile.
13. The contractor must determine the source of fresh water that will be used on the work site (Note: need to avoid using neighbouring property owners water if possible).

14. The contractor must determine where water produced during development will be disposed of.
15. The contractor must undertake site clearances for all services (rather than the Wellsite Hydrogeologist).
16. The contractor must give the Wellsite Hydrogeologist access to all areas of work site, including the steering/driving office, at all times.
17. The contractor must provide details on how frac-outs will be managed (Fig. C1).
18. The contractor must provide a site safety plan, including:
    a. Procedures on site briefing for site personnel, contractors and visitors.
    b. Appropriate fencing for site equipment (Fig. C2).
    c. Appropriate safety procedures for potential hazards (e.g. frac-outs) that may occur during drilling.
19. The contractor must provide a clear Works Method Statement to the satisfaction of DWLBC prior to signing the contract, that should include:
    a. Outline of drilling program and well construction method.
    b. Steering systems equipment to be used.
    c. Drilling equipment to be used.
    d. Specific procedures and method for major tasks, e.g.:
        i) Mud program, including:
            (1) Type of drilling fluid
            (2) Control and disposal of drilling fluids
            (3) Return of drilling fluids from exit to entry point
        ii) Drill of pilot hole
        iii) Reaming
        iv) Pull back of outer product pipe
        v) Development, including disposal of drilling fluids and water produced
        vi) Pull back of inner liner
    e. Proposals to overcome perceived problems.
    f. Ownership, or access to any specialist equipment required to construct the well (e.g. jetting tools, recovery equipment).
    g. In-house, or access to any technical expertise.

Additional notes:

1. It is recommended that Complete Pipe Systems (Callington, South Australia) be used for future jobs. This must be confirmed with the Contractor. The time required for slotting/drilling of the product pipe needs to be considered.
2. Final payment must be subject to the provision of the contractor's:
    a. Daily Drilling Reports

b. Final Well Drilling and Construction Report on the construction of the horizontal drainage well that must include:
   i) All information identified in the preceding discussion.
   ii) Details of major plant and equipment used (eg rig and specifications, pump and specifications).
   iii) Details of drilling including steering tools, drill bits, all surveying data, and problems encountered or areas of concern.
   iv) Drill Hole Log Requirements, Reaming Log Requirements, and Product Pullback Log Requirements as defined in Appendix C.
   v) Details of drilling fluids/muds, and problems encountered or areas of concern.
   vi) Details of the construction of the well, including product pipe details, and problems encountered or areas of concern.
   vii) Details of well development, including methods, tools, and problems encountered or areas of concern.

6.3 SELECTION OF DRILLING CONTRACTORS

In addition to the contract, the tendering process is also critical to the success of any drilling project, particularly where a significant amount of funds is being committed to a single well. The assessment criteria for the selection of the contractor was probably insufficiently developed, and it is suggested that the following criteria and weighting that have been developed for the construction of a similarly expensive single conventional well, be applied to such projects. While it is likely that many of the questions may not be adequately answered, contractors can be given the opportunity to expand further on their operations during interviews.

Criteria	**Weighting %**
1. Works Method Statement for construction of proposed well:-	**20**

a. Outline of drilling program and well construction method
b. Steering systems equipment to be used
c. Drilling equipment to be used
d. Specific procedures and method for major tasks, e.g.:

   i) Mud program, including:
      (1) Type of drilling fluid
      (2) Control and disposal of drilling fluids
      (3) Return of drilling fluids from exit to entry point
   ii) Drill of pilot hole
   iii) Reaming
   iv) Pull back of outer product pipe
   v) Development, including disposal of drilling fluids and water produced
   vi) Pull back of inner liner

   e. Proposals to overcome perceived problems
   f. Ownership, or access to any specialist equipment required to construct the well (e.g. jetting tools, recovery equipment)
   g. In-house, or access to any technical expertise
   h. Timeframe for work to commence

2. Demonstrated experience in horizontal drill holes in excess of 500 m, and number of holes successfully completed. **15**
3. Staff capability and experience including:- **10**
   a. Duration of employment of proposed staff with current company
   b. Duration of proposed staff working together as a team
4. Assessment of statement of non-conformity and risks/benefits in relation to:- **10**
   a. Cost
   b. Safety
   c. Technical issues
5. Adequate equipment capacity **10**
6. Cost **20**
7. Outstanding contractual disputes **10**
8. OHS&W history **5**

Total **100%**

7. CONCLUSIONS

Construction of the Loxton trial horizontal drainage well was successfully completed. This investigation clearly demonstrates that horizontal drainage wells can be installed at SIS target sites that require a horizontal drainage well application. However, the project did highlighted a number of technical and contractual issues that must be addressed in the completion of the Loxton project, and are applicable to the application of the horizontal drainage wells in other hydrogeological environments.

7.1 RECOMMENDATIONS

7.1.1 GENERAL HORIZONTAL DRAINAGE WELL CONSTRUCTION ISSUES

1. An overly thick walled outer product pipe is recommended, as this will allow a drilling rig to work over a well (if required) without severe damage to the pipe. In an extreme case of sanding of a well, a rig may be able to drill out the inner liner.
2. It is recommended that the outer product pipe be slotted/drilled to result in an open area between 1–2%, depending on the nature of the aquifer material, for discharge rates estimated to be up to 15 L/s. Regardless, the entrance velocity should conform with the nominal maximum value of 0.03 m/second applied to conventional vertical wells (although this should be reviewed and perhaps halved for horizontal wells, to reduce the potential for infiltration of mobile formation material).
3. Care should be taken during the installation of the outer product pipe to ensure that the slotted/drilled section is set solely within the target aquifer zone, and does note extend into any differing material, e.g. unconsolidated flowing sands), that may then run in the pipe. Additional blank lengths of pipe should be on hand if required.
4. A potential alternative inner liner option may be an alternating string of (say) 6 m lengths of blank HDPE and 1 m lengths of wirewound screen that can be wound at any required aperture. For a total horizontal well length of 250 m, this would result in 35 m of wirewound screen, the cost of which would be negligible in terms of the total well cost.
5. If the HDPE reversion issue can be resolved, the possibility of slotting the outer product pipe (in preference to using drill holes) should be considered, which may remove the need for an inner liner. Ideally the slots should end up 0.5–1.0 mm wide following the reversion process. Longitudinal slotting to result in an open area of 1–2% is suggested, however the possibility of radial slotting in the same configuration as was used for the inner liner in this project should be considered, if the pipe retains sufficient strength for the pullback. This more highly slotted configuration may overcome concerns regarding reversion.

7.1.2 HDPE REVERSION

If the HDPE reversion needs to be better understood then the following options exist:

1. Discuss with the pipe manufacturer (e.g. IPLEX) the possibility of minimising the reversion potential by modifying the source material, and the extrusion and cooling process. However, the pipe will still need to be laboratory tested to determine the extent of reversion that is likely to occur.
2. Alternatively the pipe can be ordered and tested, however, the extent of reversion may vary along the pipe if there has been no control on the manufacturing process, which will result in the need for multiple sections of the pipe to be laboratory tested.
3. Order the pipe, slot selected lengths, and observe the reversion for a period of several months. If the end result is acceptable, then the remaining pipe could be slotted.
4. Note that all of the above options result in a significant lead-time before drilling can commence.

7.1.3 HORIZONTAL DRAINAGE WELL FOR MONOMAN FORMATION

1. Horizontal drainage wells may be applied to the Monoman Formation with the use of a slotted liner with 0.5 mm slots cut in a similar configuration to those used in this project. It is recommended that the slot width be reduced due to the unconsolidated nature of the sands and gravels, and considerable variation in grain size that occurs in the Monoman Formation, which may cause the infiltration of sand.
2. The possibility of applying a gravel pack between the outer product pipe and inner liner has been discussed, however there would not seem to be any practical way in which this could be installed. A filter sock installed over the slotted liner may be an option, but clogging of the filter is likely to be a problem, and it is likely to be damaged during installation. A further option, may be the use of 1 m sections of wirewound screen between lengths of blank HDPE.

7.1.4 GENERAL CONTRACTUAL ISSUES

While the construction of the trial horizontal drainage well was successful, a number of issues have been identified regarding the selection of contractor and contract definition that must be addressed in future. Of particular importance is better definition of the drilling process and the requirement for the contractor to provide a final report. These issues are discussed in detail in the report.

APPENDICES

A. GEOLOGICAL LOGS

Table A1. Air-core hole LHA43 geological log

Depth Below Natural Surface (m)	Formation	Lithological Description
0–4	Woorinen Formation	Fine sand.
4–19	Loxton Sands	Medium to coarse sand; poorly sorted.
19–20	Lower Loxton Shells	Reworked shell hash and grit; poorly sorted. Shell fragments 20%.
20–25	Lower Loxton Clays	Clay with shells; shells decreasing with depth. Grey in colour.
25–29	Bookpurnong Formation	Poorly consolidated plastic silts and shelly clays. Khaki in colour.

Table A2. Air-core hole LHA42 geological log

Depth Below Natural Surface (m)	Formation	Lithological Description
0–3	Woorinen Formation	Fine sand.
3–5	Blanchetown Clay	Heavy clay, sandy in part.
5–18	Loxton Sands	Medium to coarse sand; poorly sorted.
17–22	Lower Loxton Shells	Reworked shell hash and grit; poorly sorted. Shell fragments 30%.
22–30	Bookpurnong Formation	Poorly consolidated plastic silts and shelly clays. Khaki in colour. 22–24 m shell fragments 10%; 24–25 m shell fragments >50%.

Table A3. Air-core hole LHA71 geological log

Depth Below Natural Surface (m)	Formation	Lithological Description
0–3	Woorinen Formation	Fine sand.
2–3	Calcrete	Hard bar.
3–4	Blanchetown Clay	Heavy clay, sandy in part.
4–18	Loxton Sands	Medium to coarse sand; poorly sorted.
18–21	Lower Loxton Shells	Reworked shell hash and grit; poorly sorted.
21–27	Lower Loxton Clays	Clay with shells; shells decreasing with depth. Grey in colour.

Table A4. Air-core hole LHA44 geological log

Depth Below Natural Surface (m)	Formation	Lithological Description
0–4	Woorinen Formation	Fine sand.
4–6	Blanchetown Clay	Heavy clay, sandy in part.
6–19	Loxton Sands	Medium to coarse sand; poorly sorted.
19–22	Lower Loxton Shells	Reworked shell hash and grit; poorly sorted.
24–26	Bookpurnong Formation	Poorly consolidated plastic silts and shelly clays. Khaki in colour.

Table A5. Air-core hole LHA24 geological log

Depth Below Natural Surface (m)	Formation	Lithological Description
0–5	Woorinen Formation	Fine sand.
5–18	Loxton Sands	Medium to coarse sand; poorly sorted.
18–21	Lower Loxton Shells	Reworked shell hash and grit; poorly sorted. 18–19 m shell fragments >50%; 19–21 m shell fragments <10%.
21–23	Lower Loxton Clays	Clay with shells; shells decreasing with depth. Grey in colour.
23–24	Bookpurnong Formation	Poorly consolidated plastic silts and shelly clays. Khaki in colour.

Table A6. Air-core hole LHA41 geological log

Depth Below Natural Surface (m)	Formation	Lithological Description
0–4	Woorinen Formation	Fine sand.
4–5	Blanchetown Clay	Heavy clay, sandy in part.
5–18	Loxton Sands	Medium to coarse sand; poorly sorted.
18–20	Lower Loxton Shells	Reworked shell hash and grit; poorly sorted. 18–19 m shell fragments 10–20%.
20–22	Lower Loxton Clays	Clay with shells; shells decreasing with depth. Grey in colour.
22–23	Bookpurnong Formation	Poorly consolidated plastic silts and shelly clays. Khaki in colour.

Table A7. Air-core hole LHA40 geological log

Depth Below Natural Surface (m)	Formation	Lithological Description
0–4	Woorinen Formation	Fine sand.
4–6	Blanchetown Clay	Heavy clay, sandy in part.
6–18	Loxton Sands	Medium to coarse sand; poorly sorted.
18–20	Lower Loxton Shells	Reworked shell hash and grit; poorly sorted. 18–19 m shell fragments >50%.
20–21	Lower Loxton Clays	Clay with shells; shells decreasing with depth. Grey in colour.
21–22	Bookpurnong Formation	Poorly consolidated plastic silts and shelly clays. Khaki in colour.

Table A8. Air-core hole LHA39 geological log

Depth Below Natural Surface (m)	Formation	Lithological Description
0–6	Woorinen Formation	Fine sand.
6–20	Loxton Sands	Medium to coarse sand; poorly sorted.
20–21	Lower Loxton Shells	Reworked shell hash and grit; poorly sorted. Shell fragments >50%.
21–22	Lower Loxton Clays	Clay with shells; shells decreasing with depth. Grey in colour.
22–24	Bookpurnong Formation	Poorly consolidated plastic silts and shelly clays. Khaki in colour.

Table A9. Air-core hole LHA25 geological log

Depth Below Natural Surface (m)	Formation	Lithological Description
0–3	Woorinen Formation	Fine sand.
3–7	Blanchetown Clay	Heavy clay, sandy in part.
7–21.5	Loxton Sands	Medium to coarse sand; poorly sorted.
21.5–23	Lower Loxton Shells	Reworked shell hash and grit; poorly sorted.
23–25	Lower Loxton Clays	Clay with shells; shells decreasing with depth. Grey in colour.

Table A10. Air-core hole LHA65 geological log

Depth Below Natural Surface (m)	Formation	Lithological description
0–5	Woorinen Formation	Fine sand.
5–7	Blanchetown Clay	Heavy clay, sandy in part.
7–20.5	Loxton Sands	Medium to coarse sand; poorly sorted.
20.5–21	Calcrete?	Hard bar
21–22	Lower Loxton Shells	Reworked shell hash and grit; poorly sorted.
22–25	Lower Loxton Clays	Clay with shells; shells decreasing with depth. Grey in colour.

Table A11. Air-core hole LHA38 geological log

Depth Below Natural Surface (m)	Formation	Lithological Description
0–7	Woorinen Formation	Fine sand.
7–8.5	Blanchetown Clay	Heavy clay, sandy in part.
8.5–23.5	Loxton Sands	Medium to coarse sand; poorly sorted. 22–23.5 m shell fragments.
23.5–24.5	Lower Loxton Shells	Reworked shell hash and grit; poorly sorted.
24.5–25.5	Bookpurnong Formation	Poorly consolidated plastic silts and shelly clays. Khaki in colour.

Table A12. Air-core hole LHA26 geological log

Depth Below Natural Surface (m)	Formation	Lithological description
0–5	Woorinen Formation	Fine sand.
5–8	Blanchetown Clay	Heavy clay, sandy in part.
8–20	Loxton Sands – upper unit	Medium to coarse sand; poorly sorted.
20–24	Loxton Sands – lower unit	Fine sand, silty to slightly clayey with depth.
24–25	Lower Loxton Shells	Reworked shell hash and grit; poorly sorted.
25–27	Bookpurnong Formation	Clay with shells; shells decreasing with depth. Grey in colour.

Table A13. Production well LHP47 geological log

Depth Below Natural Surface (m)	Formation	Lithological description
0–5	Woorinen Formation	Fine sand.
5–18	Loxton Sands	Medium to coarse sand; poorly sorted.
18–19	Lower Loxton Shells	Reworked shell hash and grit; poorly sorted. Shell fragments >50%.
19–22	Lower Loxton Clay	Clay with shells; shells decreasing with depth. Grey in colour.

Table A14. Production well LHP44 geological log

Depth Below Natural Surface (m)	Formation	Lithological description
0–5	Woorinen Formation	Fine sand.
5–18	Loxton Sands	Medium to coarse sand; poorly sorted.
18–19	Lower Loxton Shells	Reworked shell hash and grit; poorly sorted. Shell fragments >50%.
19–22	Lower Loxton Clay	Clay with shells; shells decreasing with depth. Grey in colour.

Table A15. Observation well LHO60 geological log

Depth Below Natural Surface (m)	Formation	Lithological description
0–5	Woorinen Formation	Fine sand.
5–6	Blanchetown Clay	Heavy clay, sandy in part.
6–22	Loxton Sands	Medium to coarse sand; poorly sorted.

Table A16. Observation well LHO44 geological log

Depth Below Natural Surface (m)	Formation	Lithological description
0–5	Woorinen Formation	Fine sand.
5–18	Loxton Sands	Medium to coarse sand; poorly sorted.
18–19	Lower Loxton Shells	Reworked shell hash and grit; poorly sorted. Shell fragments >50%
19–22	Bookpurnong Formation	Poorly consolidated plastic silts and shelly clays. Khaki in colour.

Table A17. Observation well LHO49 geological log

Depth Below Natural Surface (m)	Formation	Lithological description
0–4	Woorinen Formation	Fine sand.
4–5	Blanchetown Clay	Heavy clay, sandy in part.
5–18	Loxton Sands	Medium to coarse sand; poorly sorted.
18–19	Lower Loxton Shells	Reworked shell hash and grit; poorly sorted. Shell fragments >50%.
19–21	Bookpurnong Formation	Poorly consolidated plastic silts and shelly clays. Khaki in colour.

Table A18. Observation well LHO50 geological log

Depth Below Natural Surface (m)	Formation	Lithological description
0–4	Woorinen Formation	Fine sand.
4–5	Blanchetown Clay	Heavy clay, sandy in part.
5–18	Loxton Sands	Medium to coarse sand; poorly sorted.
18–19	Lower Loxton Shells	Reworked shell hash and grit; poorly sorted. Shell fragments >50%.
19–20	Bookpurnong Formation	Poorly consolidated plastic silts and shelly clays. Khaki in colour.

Table A19. Observation well LHO61 geological log

Depth Below Natural Surface (m)	Formation	Lithological description
0–4	Woorinen Formation	Fine sand.
4–5	Blanchetown Clay	Heavy clay, sandy in part.
5–21	Loxton Sands	Medium to coarse sand; poorly sorted.

Table A20. Observation well LHO55 geological log

Depth Below Natural Surface (m)	Formation	Lithological description
0–4	Woorinen Formation	Fine sand.
4–6	Blanchetown Clay	Heavy clay, sandy in part.
6–18	Loxton Sands	Medium to coarse sand; poorly sorted.
18–19	Lower Loxton Shells	Reworked shell hash and grit; poorly sorted. Shell fragments >50%.
19–21	Lower Loxton Clays	Clay with shells; shells decreasing with depth. Grey in colour.

Table A21. Observation well LHO62 geological log

Depth Below Natural Surface (m)	Formation	Lithological description
0–5	Woorinen Formation	Fine sand.
5–8	Blanchetown Clay	Heavy clay, sandy in part.
8–18	Loxton Sands	Medium to coarse sand; poorly sorted.
18–19	Lower Loxton Shells	Reworked shell hash and grit; poorly sorted. Shell fragments >50%.
19–22	Lower Loxton Clay	Clay with shells; shells decreasing with depth. Grey in colour.

Table A22. Observation well LHO58 geological log

Depth Below Natural Surface (m)	Formation	Lithological description
0–4.5	Woorinen Formation	Fine sand.
4.5–5	Blanchetown Clay	Heavy clay, sandy in part.
5–18	Loxton Sands	Medium to coarse sand; poorly sorted.
18–23	Lower Loxton Shells	Reworked shell hash and grit; poorly sorted. 18–19 m shell fragments >50%.

Table A23. Observation well LHO63 geological log

Depth Below Natural Surface (m)	Formation	Lithological description
0–3.5	Woorinen Formation	Fine sand.
3.5–6	Blanchetown Clay	Heavy clay, sandy in part.
6–19	Loxton Sands	Medium to coarse sand; poorly sorted.
19–22.5	Lower Loxton Shells	Reworked shell hash and grit; poorly sorted. 19–20 m shell fragments >50%; 20–22.5 m shell fragments <5%.
22.5–24	Bookpurnong Formation	Poorly consolidated plastic silts and shelly clays. Khaki in colour.

Table A24. Observation well LHO59 geological log

Depth Below Natural Surface (m)	Formation	Lithological description
0–5	Woorinen Formation	Fine sand.
5–6	Blanchetown Clay	Heavy clay, sandy in part.
6–20	Loxton Sands	Medium to coarse sand; poorly sorted.
20–21	Lower Loxton Shells	Reworked shell hash and grit; poorly sorted. Shell fragments >50%.

Table A25. Observation well LHO64 geological log

Depth Below Natural Surface (m)	Formation	Lithological description
0–3.5	Woorinen Formation	Fine sand.
3.5–6	Blanchetown Clay	Heavy clay, sandy in part.
6–19.3	Loxton Sands	Medium to coarse sand; poorly sorted. 19–19.3 m well cemented sandstone with minor shell fragments and slightly calcareous cement. Thin veins apparent. Could not penetrate.

B. HDD EQUIPMENT

LUCAS

American Augers DD-140B Directional Drilling Rig

Max. Rotary Speed:
95 RPM
Other Features:
Rear mounted mud swivel, 3" (76 mm) internal diameter, dual drive brakes, slip sub, digital tachometer, wireline commutator, 5-1/2" API full hole box connection, adjustable torque limiter.

Carriage Drive

Max. Thrust/Pullback:
140,000 lb (622.7 kN).
Cariage System:
Rack and pinion, four pinion drive,
with adjustable force limiter.
Max. Carriage Speed:
95 ft (29 m)/min.
Drill Rig
Wrench/Clamp:
Open top type, 10" (254mm) separation. Wrench can travel 60" (1,524 mm) fore and aft.
Max. Breakout Torque:
60,000 ft-lb (81,360Nm).

Clamp Grip Range:
2-3/4 - 10-3/4" outside diameter.
Operator's Controls:
Rig mounted console with gauges.
Drill Angle:
10 degree - 18 degree.
Travel system:
Self propelled on Caterpillar 320L excavator tracks.
Drill Mounted Crane:
8,000 lb (3,629kg) rating.
Shipping Weight:
58,000 lb (26,300 kg).
Hold Down Stakes:
H-beam type.

Engine

Engine Type:
Caterpillar 3306 6-cylinder turbodiesel, aftercooled.
Rating:
300 HP (224 kW) continuous duty. Fuel Capacity:150 U.S. Gallons (568litres).

Rotary Drive

Rotary System:
Pinion and gear drive.
Infinitely variable torque.
Rotary (high torque):
25,000 ft-lb (33,900 Nm) @ 0-45 RPM
Rotary (low torque):
10,000 ft-lb (13,560 Nm) @ 0-95 RPM

Figure B1. American Augers DD-140B directional drilling rig

Figure B2. Steering/driller control office

C. HDD MANAGEMENT, DRILL HOLE MONITORING AND OH&S STRATEGIES

Table C1. Drill hole log requirements

Project: …………………….

Contractor: …………………….

Drill Rig: ……………………. Driller: ……………………. Steerer: ……………………. Date: ……….

Drill bit configuration: …………………….

Type of steering tool: …………………….

Interference

Yes ………. No ……….

Rod No	Rod Length	Rod Diameter	Distance (m)	Depth (m)	Pitch	Ave Rotary Torque	Steer Direction	Ave Thrust Pressure	Mud (m3/min)	Rate of Penetra-tion	Comment
1											
2											
3											
4											
5											

Table C2. Reaming log requirements

Project: …………………….

Contractor: …………………….

Drill Rig: ……………………. Driller: ……………………. Date: ……….

Reaming tool configuration (log must be completed for each pass / tool): ……………………………………………

Reaming tool diameter: …………………….

Method of reaming (eg forward ream / ream and push out etc): ………………………………………………………

Free rotational pressure prior to reaming: ………………………..

Pass number: ……………………

Rod No	Rod Length	Rod Diameter	Distance (m)	Ave Rotary Torque	Penetration Rate	Fluid Pressure (PSI)	Mud (m^3/min)	Comment
1								
2								
3								
4								
5								

If last reaming pass, percentage of solids prior to product pullback: ………………………

Table C3. Product pullback log requirements

Project: …………………….

Contractor: …………………….

Drill Rig: ……………………. Driller: ……………………. Date: ……….

Pulling head configuration (eg barrel reamer, swivel joint with outer HDPE threaded to head and fusion welded to product string): …………………………………………………………………………………………………...

Product outer diameter: …………………….

Percentage of solids in drilling fluid prior to pullback: ………………………..

Maximum pullback pressure allowable (not including safety factor), considering after-market slotting or drilling operations: ……………………………………………………………………….

Rod No	Rod Length	Rod Diameter	Distance (m)	Ave pulling force or pressure applied to Product	Maximum pulling force or pressure applied to Product	Penetration Rate	Comment
1							
2							
3							
4							
5							

Figure C1. Frac-out management strategy

Figure C2. Site safety fencing

UNITS OF MEASUREMENT

Units of measurement commonly used (SI and non-SI Australian legal)

Name of unit	Symbol	Definition in terms of other metric units	Quantity
day	d	24 h	time interval
gigalitre	GL	10^6 m^3	volume
gram	g	10^{-3} kg	mass
hectare	ha	10^4 m^2	area
hour	h	60 min	time interval
kilogram	kg	base unit	mass
kilolitre	kL	1 m^3	volume
kilometre	km	10^3 m	length
litre	L	10^{-3} m^3	volume
megalitre	ML	10^3 m^3	volume
metre	m	base unit	length
microgram	µg	10^{-6} g	mass
microlitre	µL	10^{-9} m^3	volume
milligram	mg	10^{-3} g	mass
millilitre	mL	10^{-6} m^3	volume
millimetre	mm	10^{-3} m	length
minute	min	60 s	time interval
second	s	base unit	time interval
tonne	t	1000 kg	mass
year	y	356 or 366 days	time interval

AHD	Australian Height Datum
EC	Electrical Conductivity (µS/cm)
GDA	Geocentric Datum of Australia
HDD	Horizontal Directional Drilling
HDPE	High-density polyethylene
pH	acidity
ppm	parts per million
ppb	parts per billion
TDS	Total Dissolved Solids (mg/L)

GLOSSARY

Act (the). In this document, refers to The *Natural Resources Management Act* (South Australia) 2004.

Aquifer. An underground layer of rock or sediment which holds water and allows water to percolate through.

Aquifer, confined. Aquifer in which the upper surface is impervious and the water is held at greater than atmospheric pressure. Water in a penetrating well will rise above the surface of the aquifer.

Aquifer test. A hydrological test performed on a well, aimed to increase the understanding of the aquifer properties, including any interference between wells, and to more accurately estimate the sustainable use of the water resource available for development from the well.

Aquifer, unconfined. Aquifer in which the upper surface has free connection to the ground surface and the water surface is at atmospheric pressure.

Aquitard. A layer in the geological profile that separates two aquifers and restricts the flow between them.

Baseflow. The water in a stream that results from groundwater discharge to the stream. (This discharge often maintains flows during seasonal dry periods and has important ecological functions.)

Bore. *See well.*

Catchment. A catchment is that area of land determined by topographic features within which rainfall will contribute to runoff at a particular point.

Codes of practice. Standards of management developed by industry and government, promoting techniques or methods of environmental management by which environmental objectives may be achieved.

Cone of depression. An inverted cone-shaped space within an aquifer caused by a rate of groundwater extraction which exceeds the rate of recharge. Continuing extraction of water can extend the area and may affect the viability of adjacent wells, due to declining water levels or water quality.

DSS. Dissolved suspended solids.

DWLBC. Department of Water, Land and Biodiversity Conservation. Government of South Australia.

EC. Abbreviation for electrical conductivity. 1 EC unit = 1 micro-Siemen per centimetre (µS/cm) measured at 25 degrees Celsius. Commonly used to indicate the salinity of water.

Environmental values. The uses of the environment that are recognised as of value to the community. This concept is used in setting water quality objectives under the Environment Protection (Water Quality) Policy, which recognises five environmental values — protection of aquatic ecosystems, recreational water use and aesthetics, potable (drinking water) use, agricultural and aquaculture use, and industrial use. It is not the same as ecological values, which are about the elements and functions of ecosystems.

EPA. Environment Protection Agency.

Evapotranspiration. The total loss of water as a result of transpiration from plants and evaporation from land, and surface waterbodies.

GL. *See gigalitre.*

Geological features. Include geological monuments, landscape amenity and the substrate of land systems and ecosystems.

Ground surface. Also called the natural surface.

Groundwater. *See underground water.*

HDPE. High-density polyethylene.

Hydrogeology. The study of groundwater, which includes its occurrence, recharge and discharge processes and the properties of aquifers. *(See hydrology.)*

Hydrology. The study of the characteristics, occurrence, movement and utilisation of water on and below the earth's surface and within its atmosphere. *(See hydrogeology.)*

Infrastructure. Artificial lakes; or dams or reservoirs; or embankments, walls, channels or other works; or buildings or structures; or pipes, machinery or other equipment.

Irrigation. Watering land by any means for the purpose of growing plants.

Irrigation season. The period in which major irrigation diversions occur, usually starting in August–September and ending in April–May.

Lake. A natural lake, pond, lagoon, wetland or spring (whether modified or not) and includes: part of a lake; and a body of water declared by regulation to be a lake; a reference to a lake is a reference to either the bed, banks and shores of the lake or the water for the time being held by the bed, banks and shores of the lake, or both, depending on the context.

Land. Whether under water or not and includes an interest in land and any building or structure fixed to the land.

Local water management plan. A plan prepared by a council and adopted by the Minister in accordance with Part 7, Division 4 of the Act.

MDBC. Murray-Darling Basin Commission.

Megalitre (ML). One million litres (1 000 000).

ML. *See megalitre.*

Model. A conceptual or mathematical means of understanding elements of the real world which allows for predictions of outcomes given certain conditions. Examples include estimating storm runoff, assessing the impacts of dams or predicting ecological response to environmental change.

Natural recharge. The infiltration of water into an aquifer from the surface (rainfall, streamflow, irrigation etc.) *(See recharge area, artificial recharge.)*

Natural Resources. Soil; water resources; geological features and landscapes; native vegetation, native animals and other native organisms; ecosystems.

Natural Resources Management (NRM). All activities that involve the use or development of natural resources and/or that impact on the state and condition of natural resources, whether positively or negatively.

Permeability. A measure of the ease with which water flows through an aquifer or aquitard.

PIRSA. (Department of) Primary Industries and Resources South Australia.

Potable water. Water suitable for human consumption.

Potentiometric head. The potentiometric head or surface is the level to which water rises in a well due to water pressure in the aquifer.

PWA. Prescribed Wells Area.

PWCA. Prescribed Watercourse Area.

PWRA. Prescribed Water Resources Area.

Recharge area. The area of land from which water from the surface (rainfall, streamflow, irrigation, etc.) infiltrates into an aquifer. *(See artificial recharge, natural recharge.)*

Rehabilitation (of waterbodies). Actions that improve the ecological health of a waterbody by reinstating important elements of the environment that existed prior to European settlement.

Surface water. (a) water flowing over land (except in a watercourse), (i) after having fallen as rain or hail or having precipitated in any another manner, (ii) or after rising to the surface naturally from underground; (b) water of the kind referred to in paragraph (a) that has been collected in a dam or reservoir.

Underground water (groundwater). Water occurring naturally below ground level or water pumped, diverted or released into a well for storage underground.

Waterbody. Waterbodies include watercourses, riparian zones, floodplains, wetlands, estuaries, lakes and groundwater aquifers.

Watercourse. A river, creek or other natural watercourse (whether modified or not) and includes: a dam or reservoir that collects water flowing in a watercourse; and a lake through which water flows; and a channel (but not a channel declared by regulation to be excluded from the this definition) into which the water of a watercourse has been diverted; and part of a watercourse.

Well. (a) an opening in the ground excavated for the purpose of obtaining access to underground water; (b) an opening in the ground excavated for some other purpose but that gives access to underground water; (c) a natural opening in the ground that gives access to underground water.

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